Optical Time Projection Chambers: A New Look at Dark Matter & Neutrino Physics

Jocelyn Monroe,
Royal Holloway University of London

Department of Physics Seminar,
Kyoto University
Dec. 9, 2016

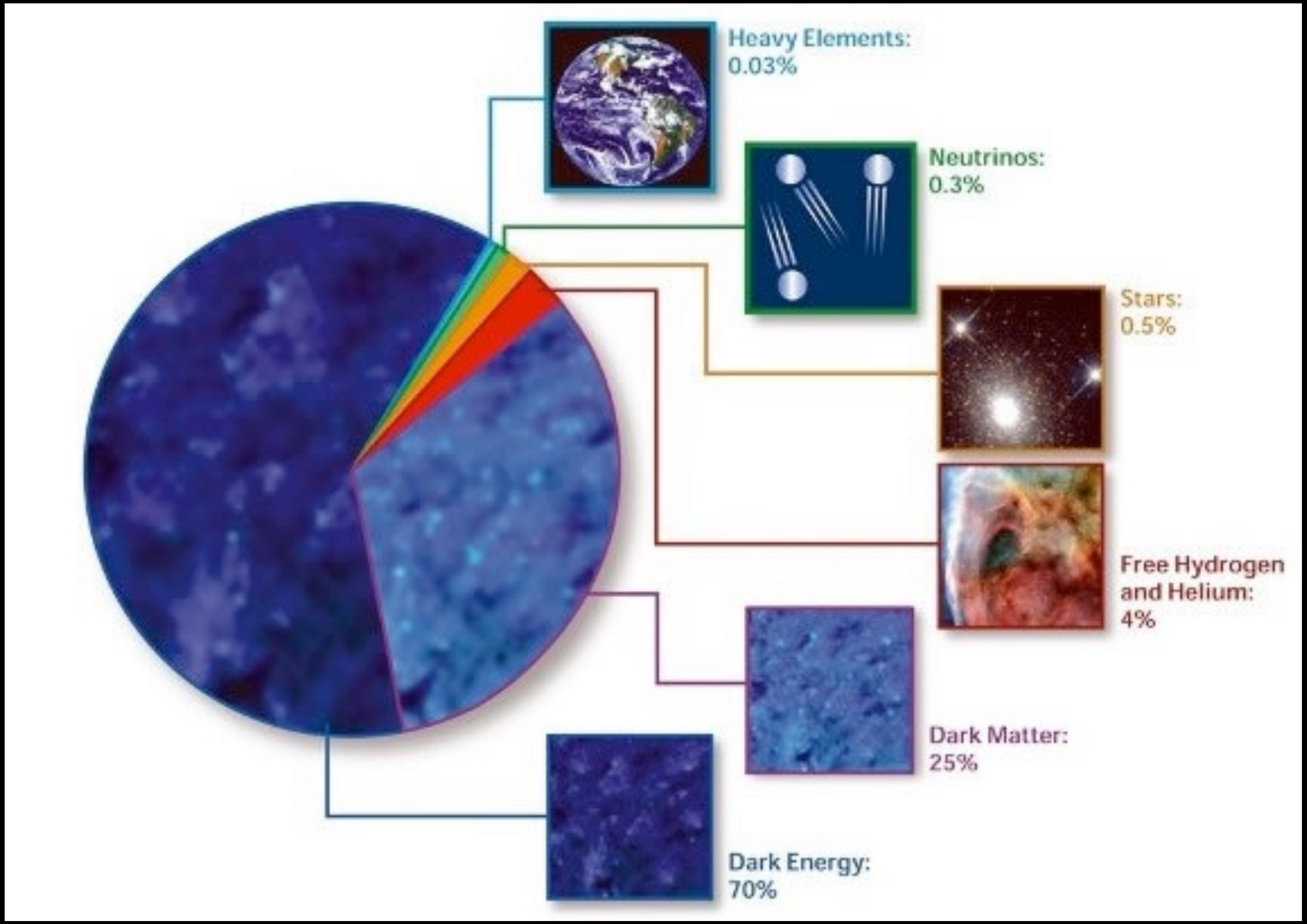
Outline

Physics Motivation

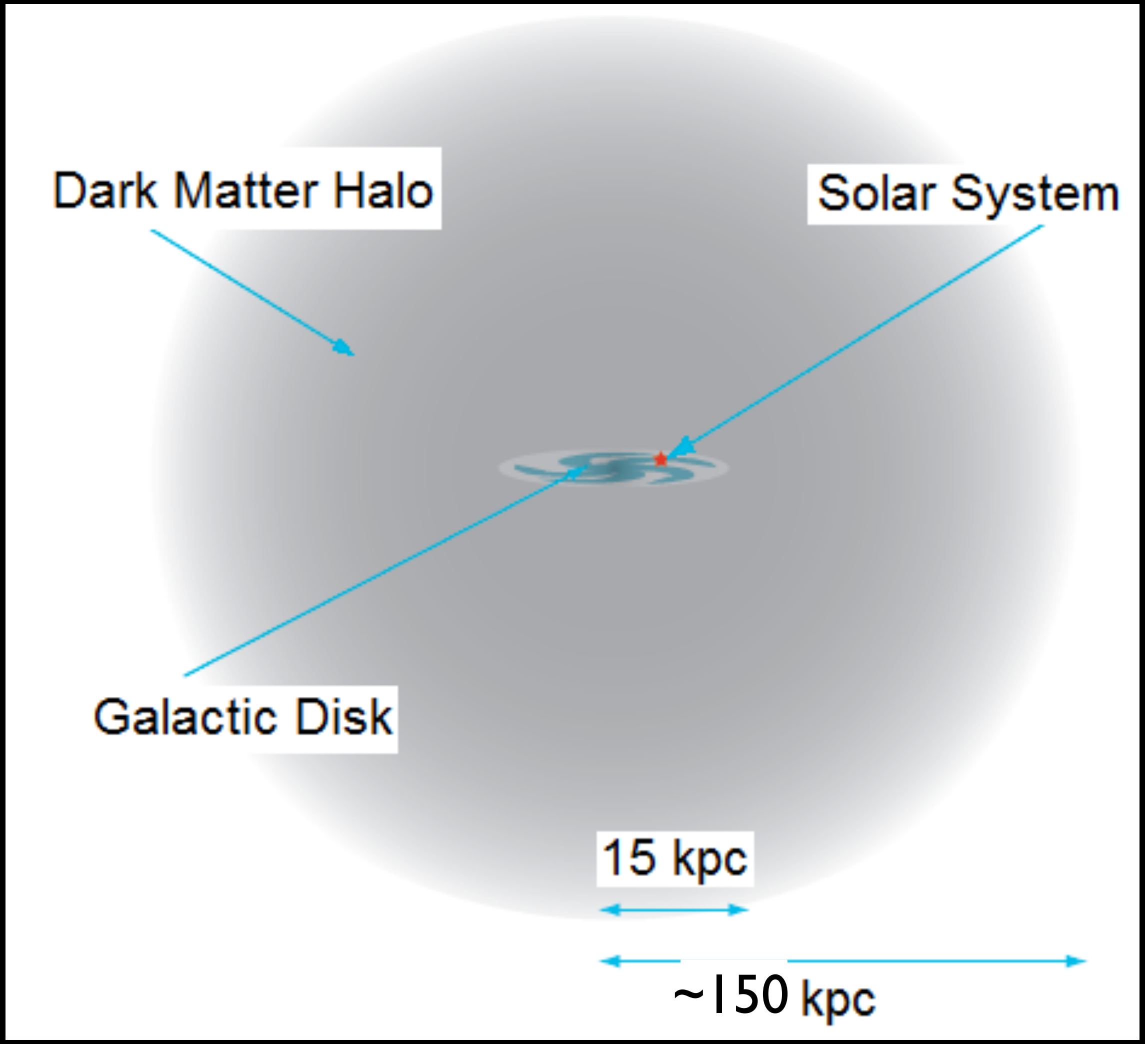
Detector Development for Dark Matter
-Experimental Considerations
-Direction Measurement Progress in DMTPC

Outlook for Large Detectors
-Geo-Neutrino Sensitivity
-HPTPC for Neutrino Physics

Dark Matter is ~25% of the energy density of the universe.



What do we know about Dark Matter?



optically dark

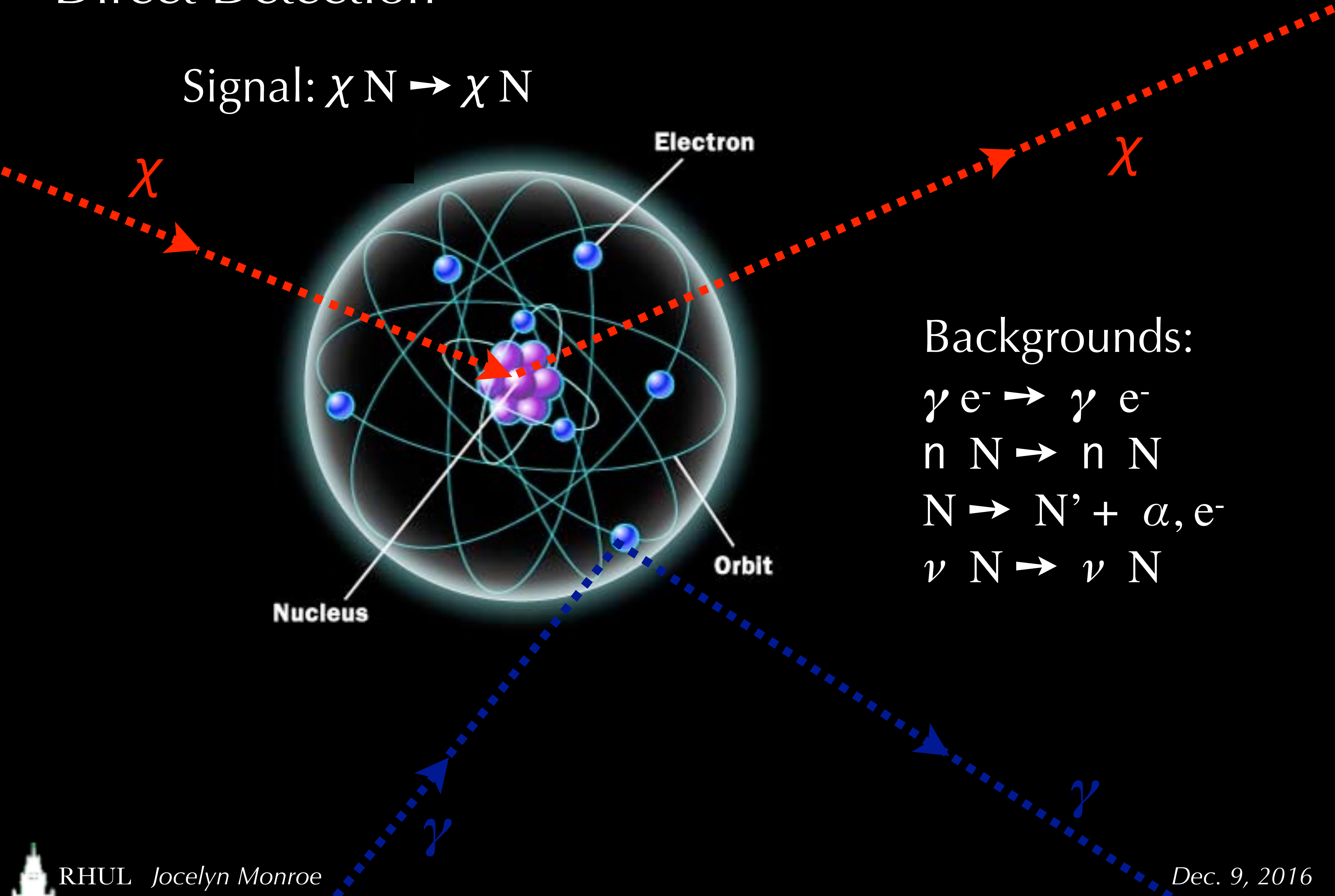
density ~ 0.3 GeV/cm^3

dark matter particle mass: ~unknown

interactions: very weak, ~collision-less

Direct Detection

Signal: χ N → χ N



Backgrounds:

γ e^- → γ e^-

n N → n N

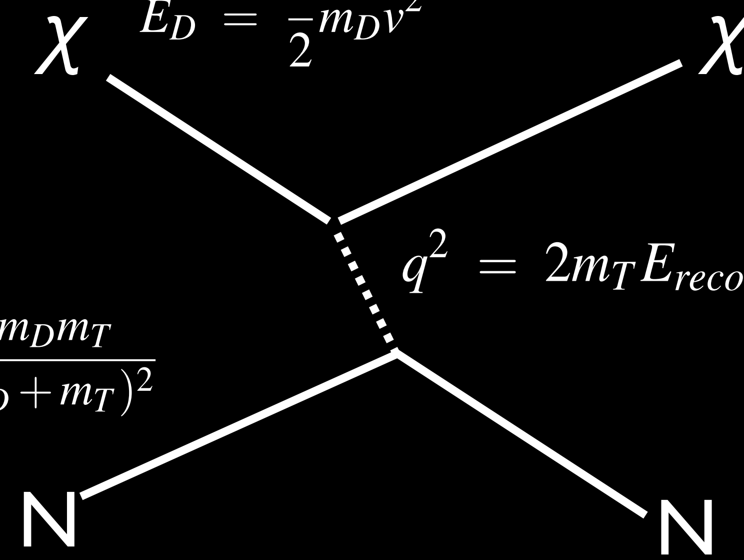
N → N' + α, e^-

ν N → ν N

WIMP Scattering

kinematics: *v/c ~ 8E-4!*

recoil angle strongly correlated with incoming WIMP direction



$$E_D = \frac{1}{2} m_D v^2$$

$$q^2 = 2 m_T E_{recoil}$$

$$r = \frac{4 m_D m_T}{(m_D + m_T)^2}$$

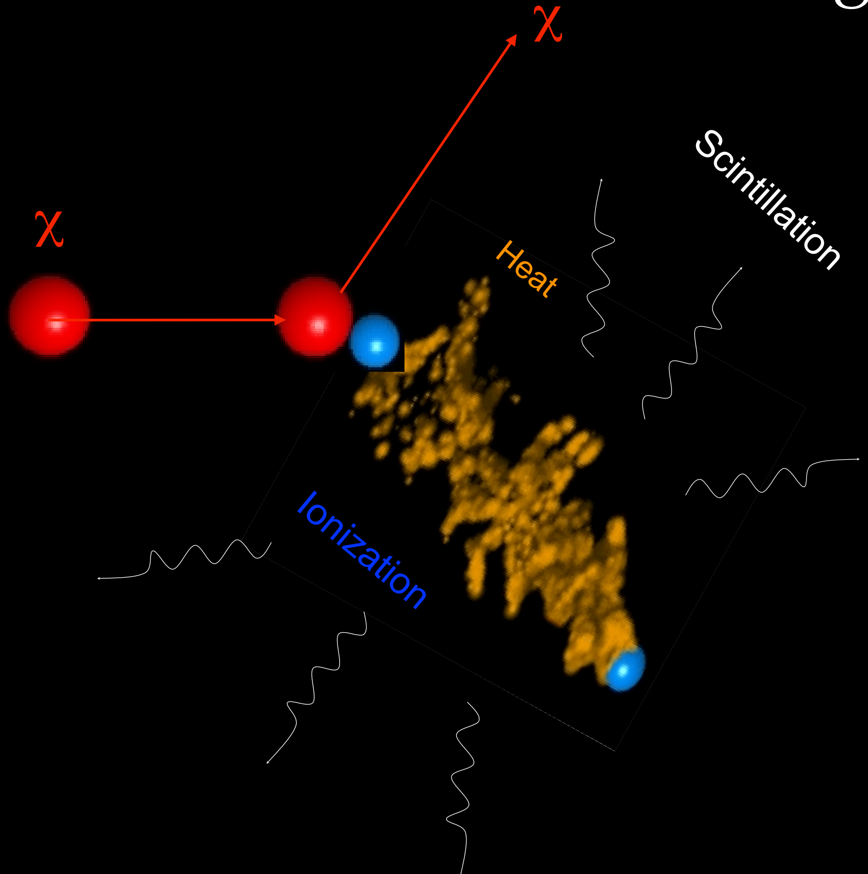
$$E_{recoil} = E_D r \frac{(1 - cos\theta)}{2}$$

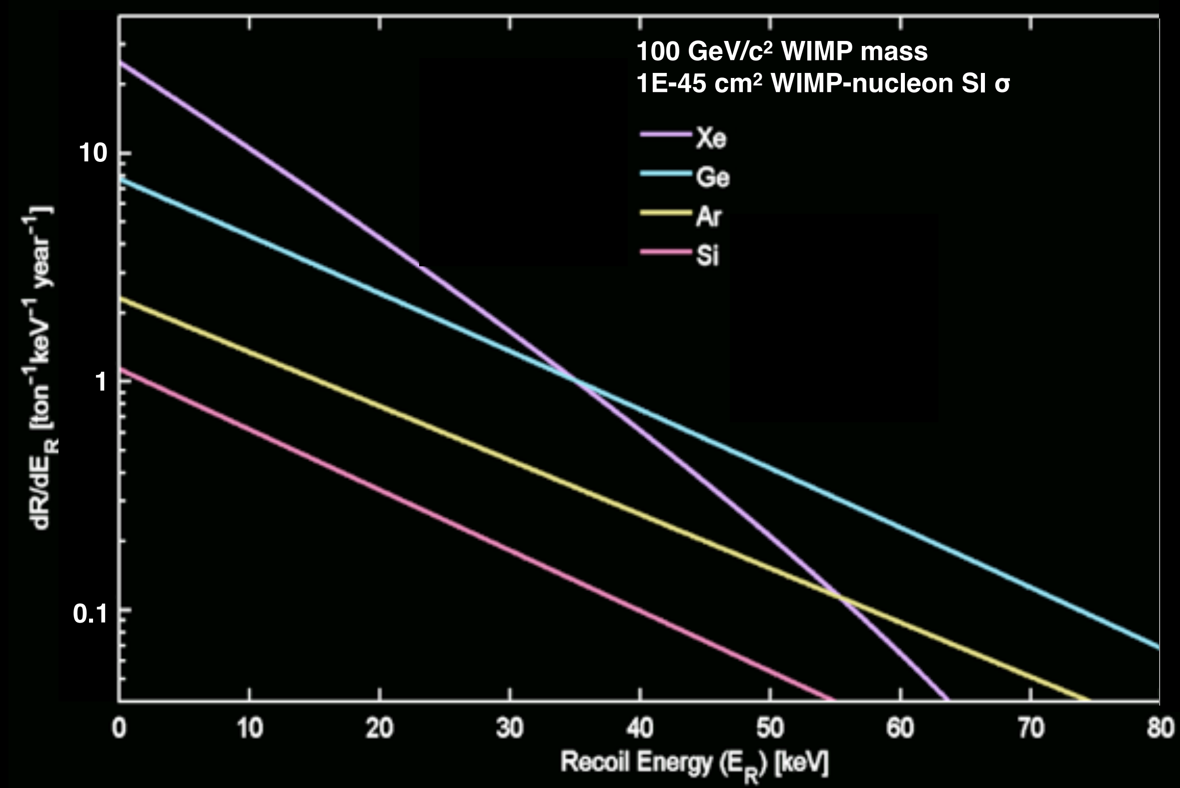
<u>Spin Independent:</u>
χ scatters coherently off of the entire nucleus A: σ~A^2
D. Z. Freedman, PRD 9, 1389 (1974)

<u>Spin Dependent:</u>
mainly unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

detector requirements: measure recoil energy, time, +angle

Observable: Recoil Energy





Scattering rate

Sun's velocity around the galaxy

WIMP velocity distribution

$$dR/dQ \sim (\sigma_0 \rho_0 / \sqrt{\pi}\, v_0 m_\chi m_r^2)\, F^2(Q)\, T(Q)$$

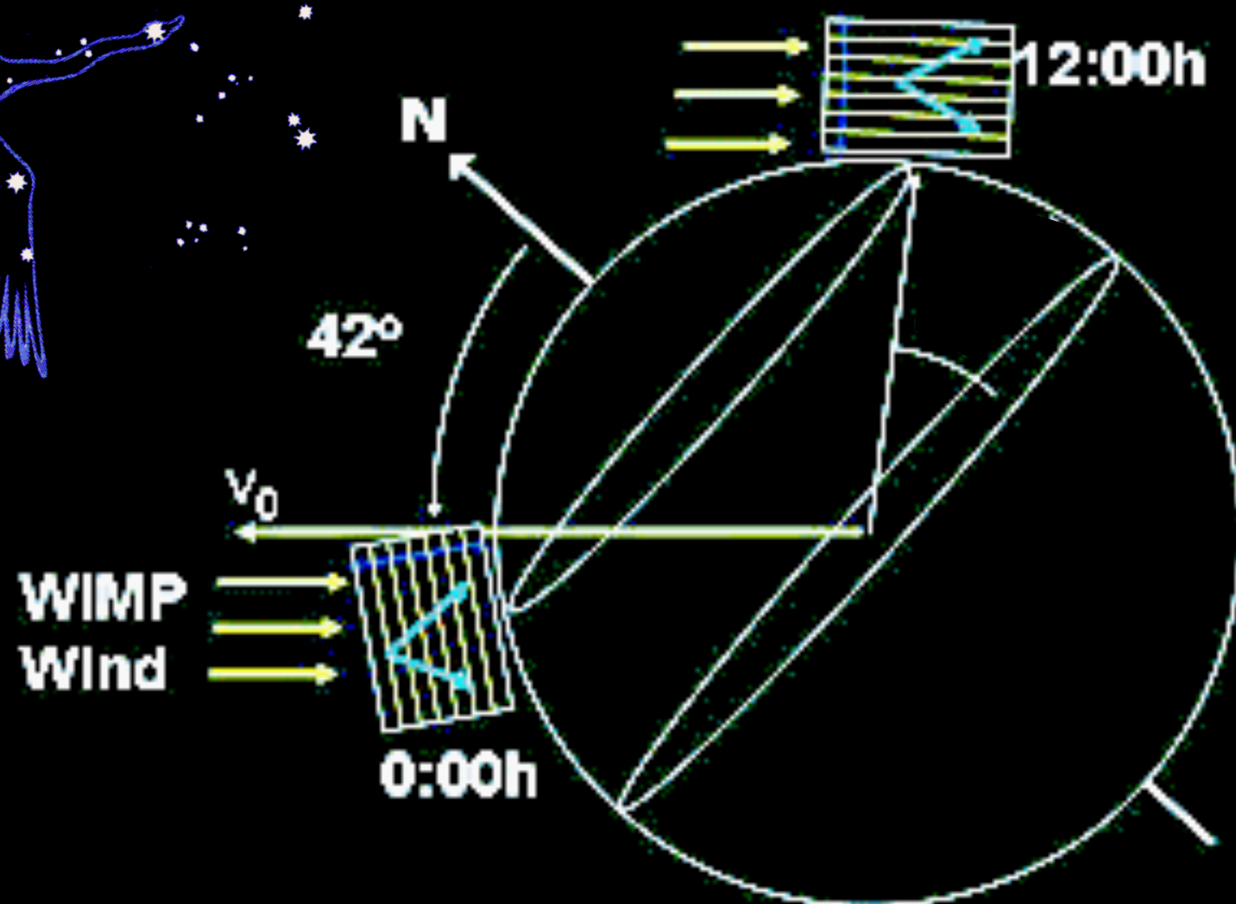
WIMP energy density, 0.3 GeV/cm³

Form factor

detector requirements: ~1-10s of keV energy threshold, background rates << 1/kg-yr

The Dark Matter Wind apparently "blows" from Cygnus

directional detection:
search for a dark matter source



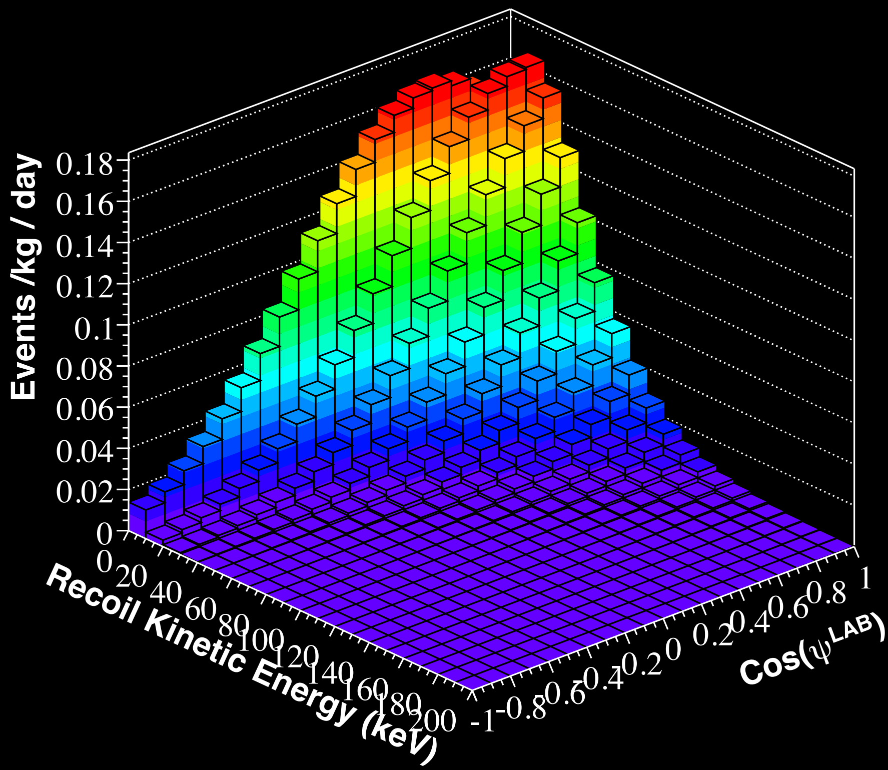
Daily direction modulation:
asymmetry ~ 20-100%
in forward-backward
event rate.

Spergel, Phys. Rev. D36:1353 (1988)

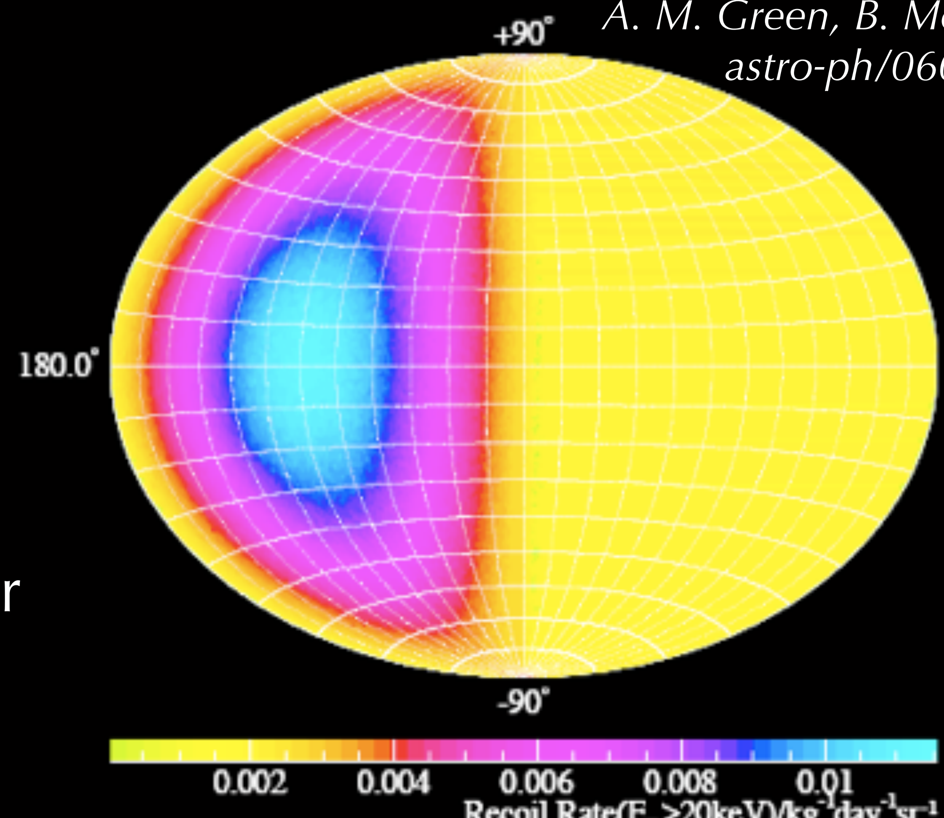
Unambiguous proof:
Correlation of WIMP-induced nuclear recoil signal with galactic motion

Directional Detection Goal

if you can reconstruct the energy and *angle* of the recoil nucleus,
you have **a dark matter telescope**



A. M. Green, B. Morgan, astro-ph/0609115



simulated reconstructed dark matter sky map: search for anisotropy

Signal characteristics:
(i) forward-backward asymmetry in galactic frame, (ii) sidereal modulation in lab

Outline

Physics Motivation

Detector Development
-Experimental Considerations for Dark Matter Searches
-Direction Measurement Progress in DMTPC

Outlook for Large Exposure
-Geo-Neutrino Sensitivity
-HPTPC for Neutrino Physics

Optimization

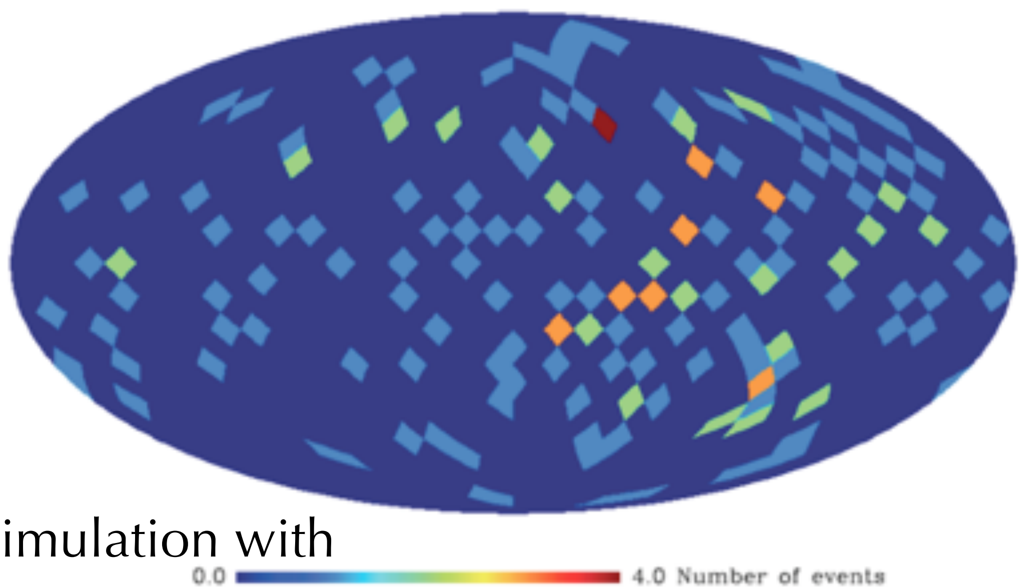
how many events to detect the dark matter wind?

<u>Detector Properties:</u>

energy threshold
background
reconstruction
(2D vs. 3D)
vector or axial
reconstruction

No background, 3-d vector read-out, $E_T = 20$ keV	5
$E_T = 50$ keV	5
$E_T = 100$ keV	3
$S/N = 10$	8
$S/N = 1$	17
$S/N = 0.1$	99
3-d axial read-out	81
2-d vector read-out in optimal plane, reduced angles	12
2-d axial read-out in optimal plane, reduced angles	190

*Perfect Case
(no detector effects)



simulation with
100 signal, 100 background

Billard et al. 2010

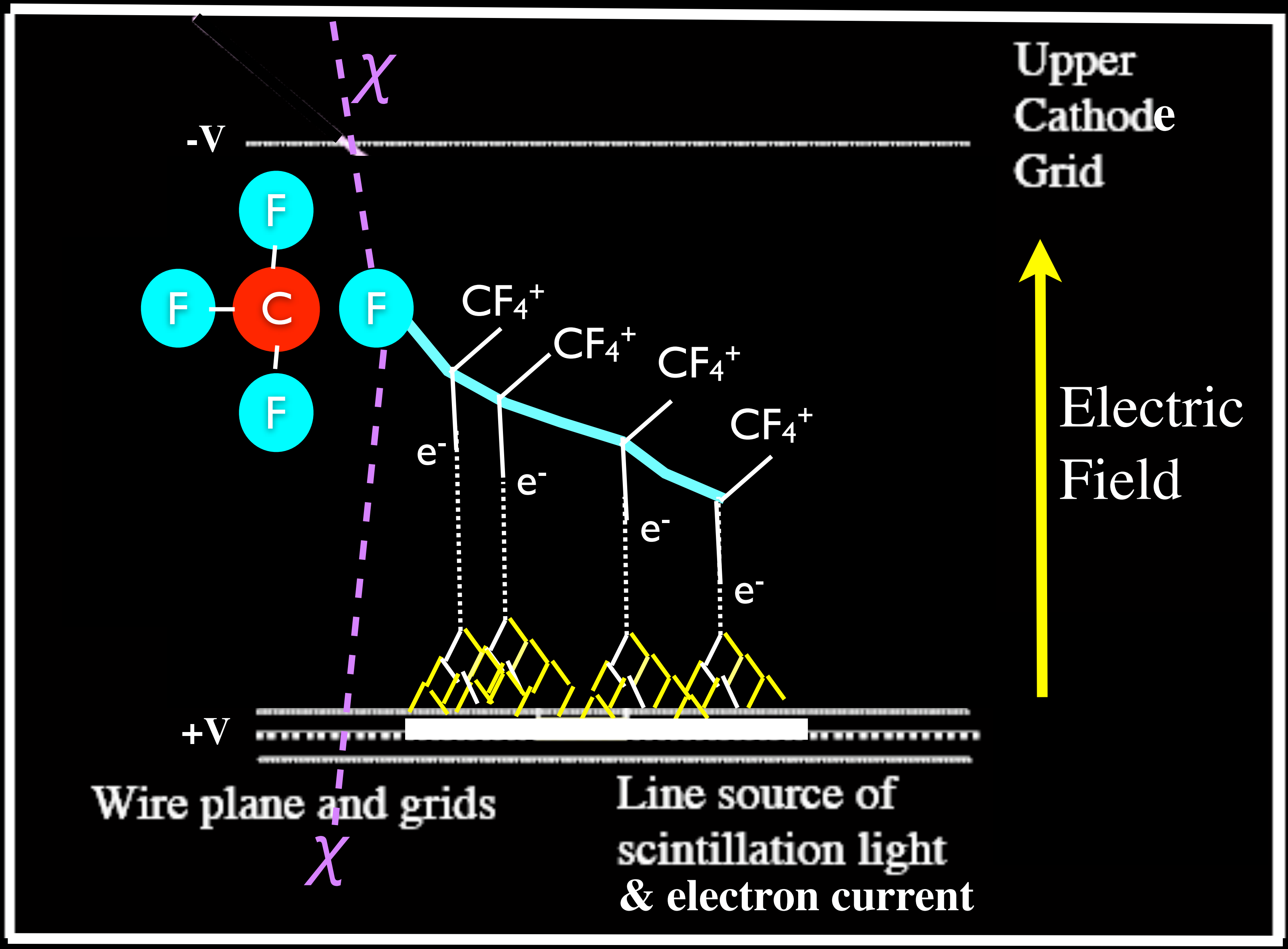
*A. M. Green, B. Morgan,
Astropart.Phys.27:142-149,2007*

*J. Billard, F. Mayet, D. Santos,
EAS Publ.Ser.53 (2012) 67-75*

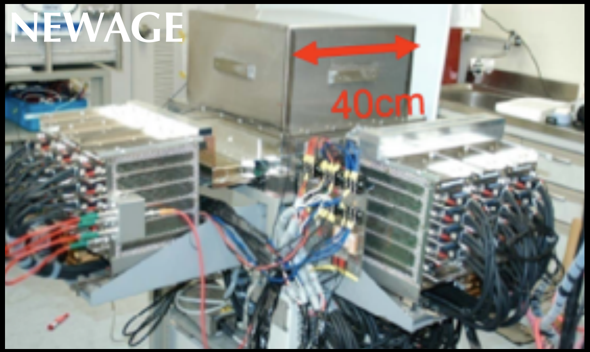
do not need "zero background" for directional detectors

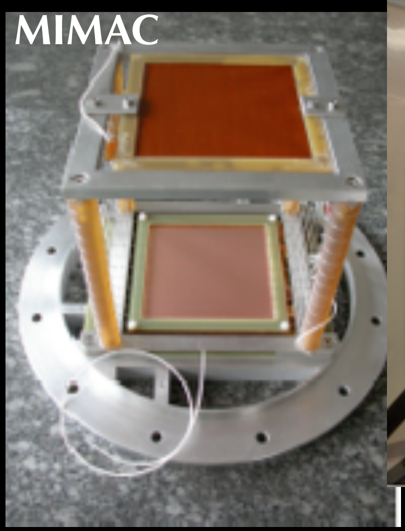
F. Mayet, JM, et al. arXiv:1602.03781

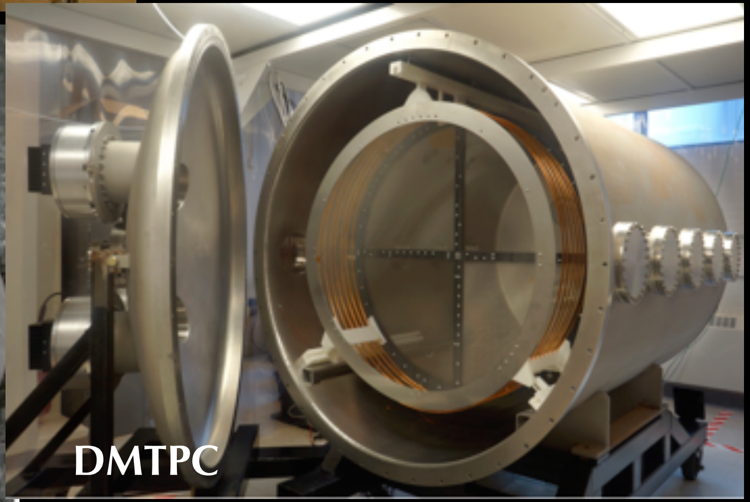
TPC Directional Detectors



Directional R&D Around the World







DRIFT: MWPC readout, operating $0.8m^3$ detector in Boulby since 2001. Negative ion drift of CS_2+CF_4.
S. Burgos et al., Astropart. Phys. 28, 409 (2007)

NEWAGE: mu-PIX readout of CF_4 target, in Kamioka. First directional limit.
K. Miuchi, et al., Phys.Lett.B654:58-64 (2007)

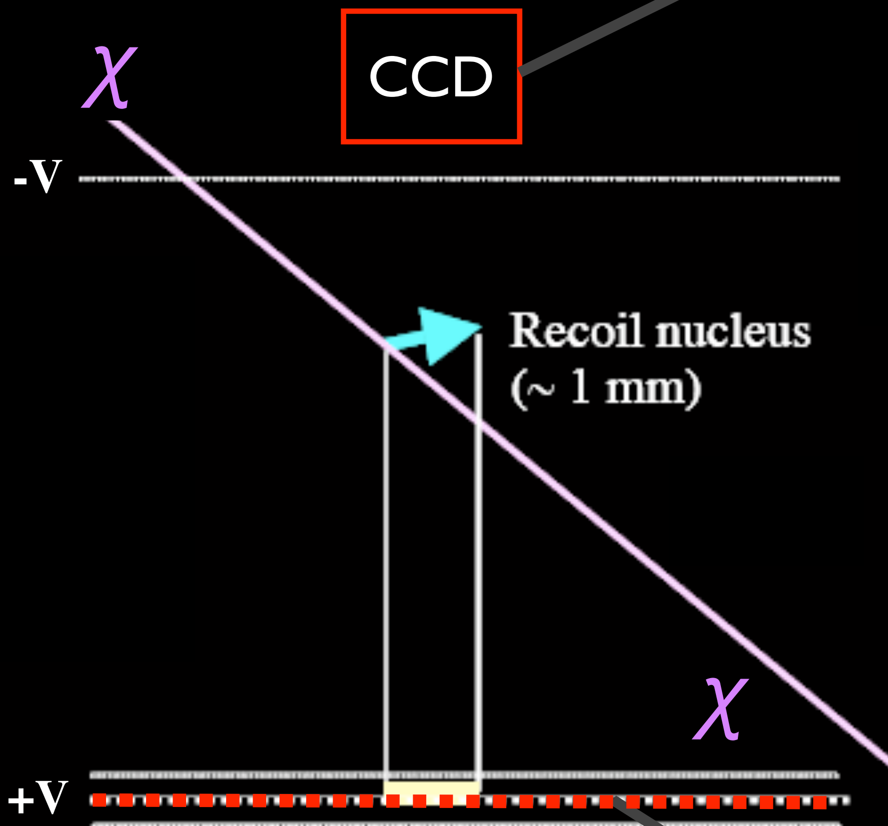
MIMAC: micromegas readout of CF_4 target, in Modane. Focus on low energy.
D. Santos, et al., J. Phys. Conf. 65, 021012 (2007)

DMTPC: optical (CCD) and charge readout of CF_4 targe, commissioning $1m^3$ module. 2D + 1D, focus on vector direction.
D. Dujmic, JM, et al., NIM A 584:337 (2008)

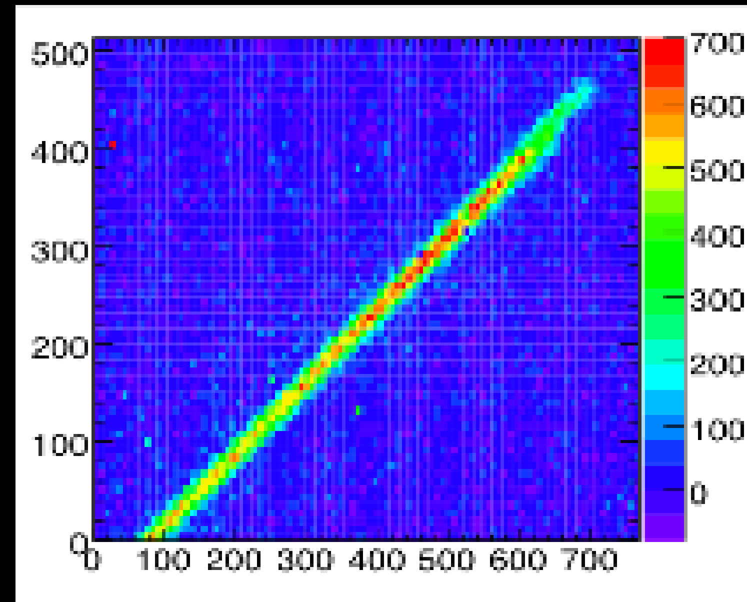
CYGNUS: coordination of directional R&D

plus R&D on fine-grained emulsions, pixel chips, high P gas, biological detectors, C nanotubes, ++

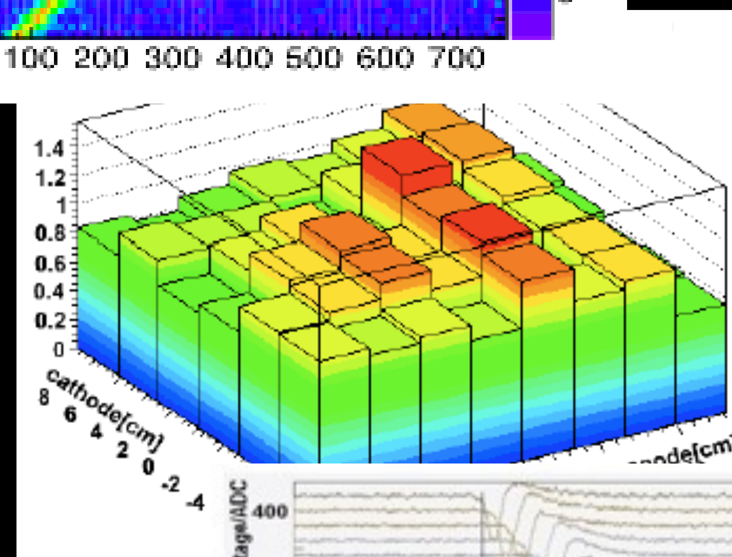
Photon Signal



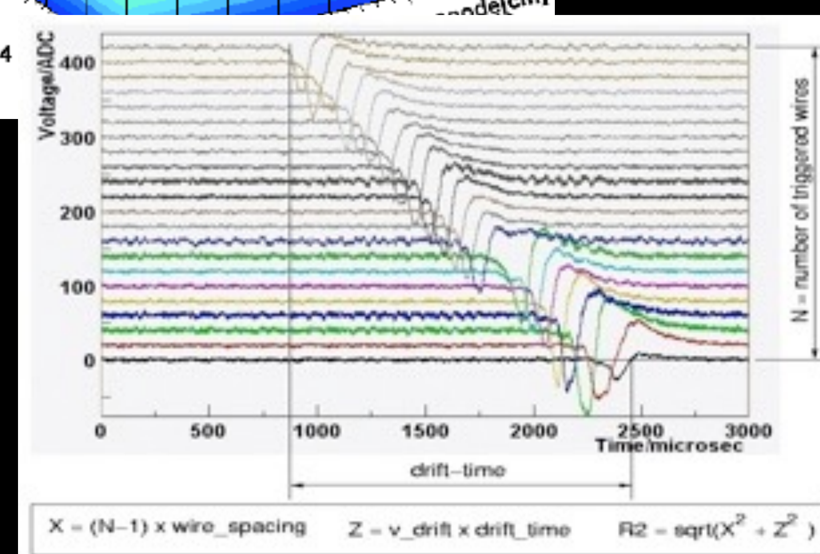
Electron/Ion Signal



Optical Readout (DMTPC)



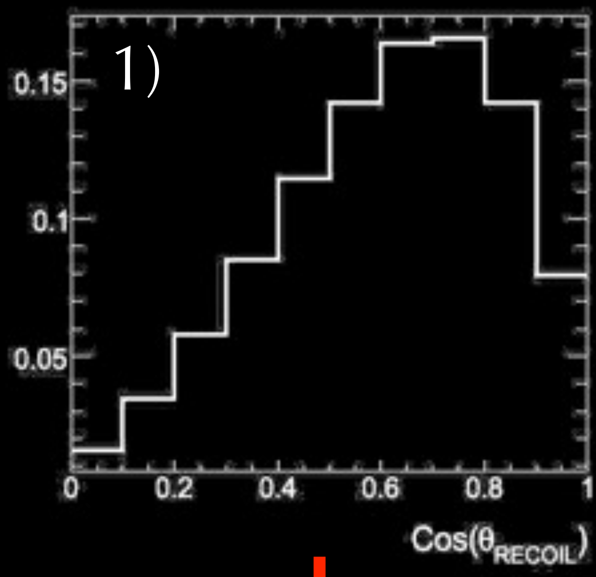
Charge Readout (NEWAGE, MIMAC)



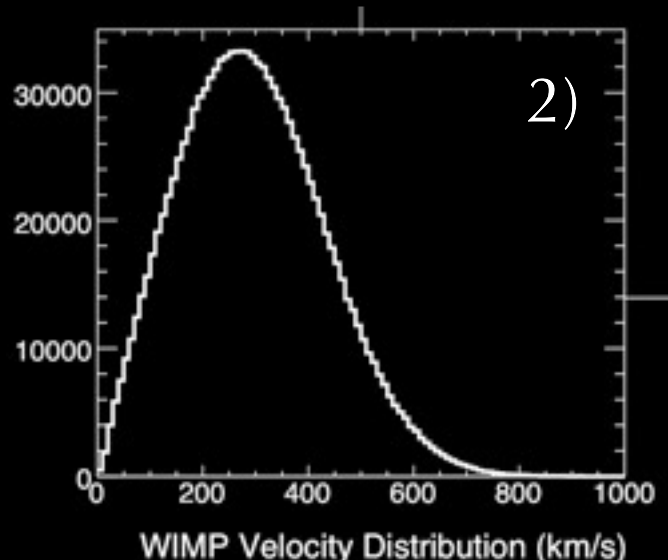
MWPC Readout (DRIFT)

Directional Detection Whitepaper: arXiv:0911.0323

Dark Matter-Induced Recoil Signal Direction



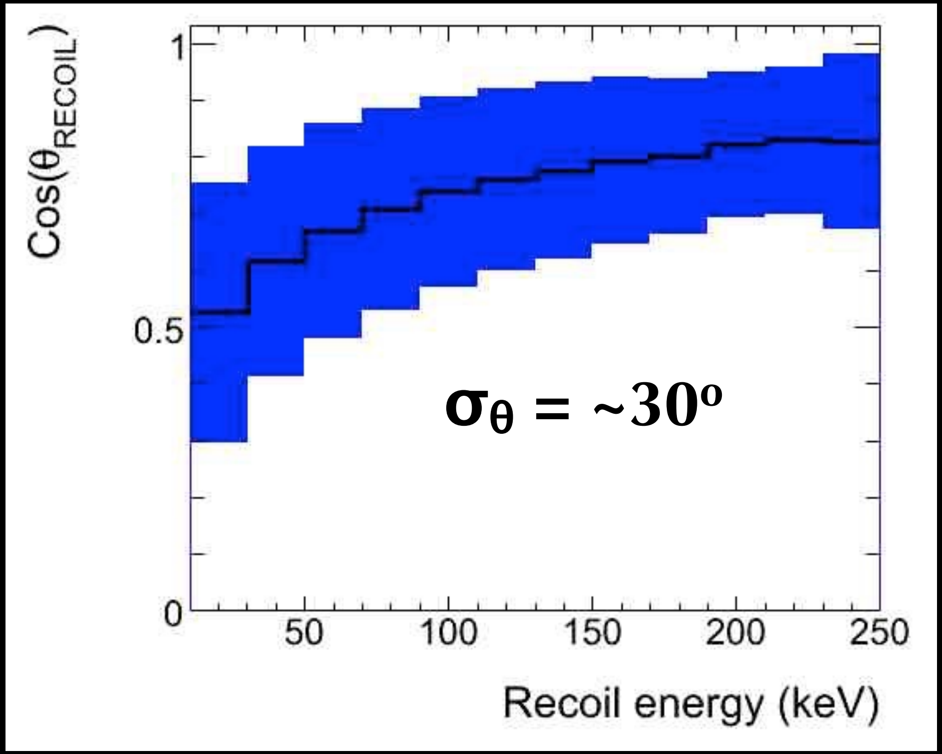
+



distribution of signal events determined by:

1. angular resolution of elastic scattering
2. dark matter velocity dispersion

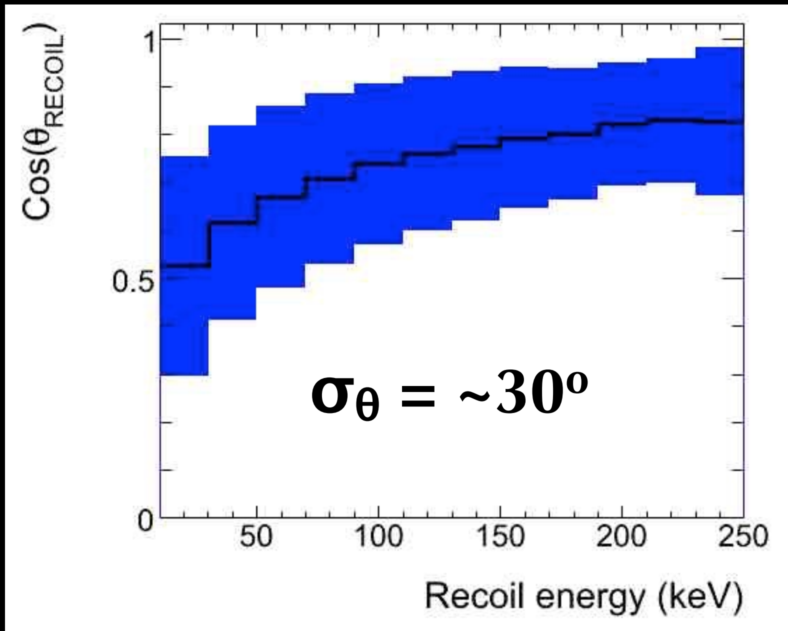
=



for 100 GeV WIMPs, need ~50 keV energy threshold for direction anisotropy at 3σ

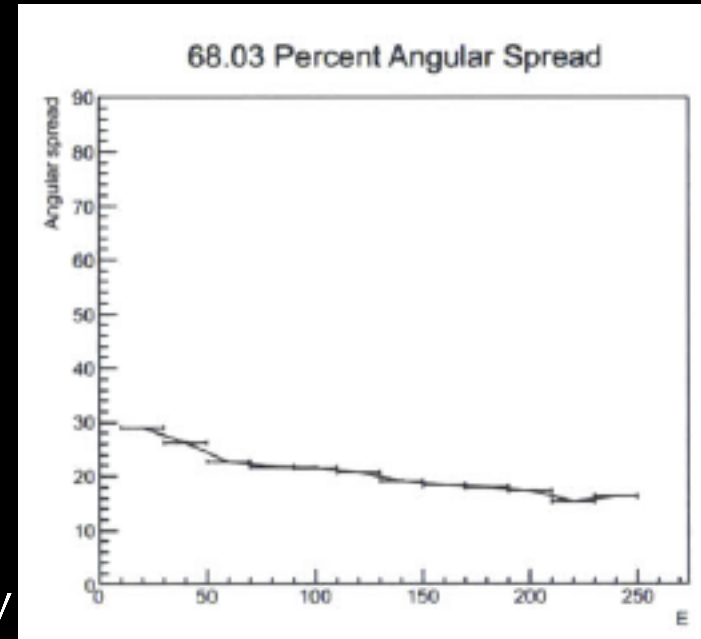
Impact of Detector Physics on Signal Directionality

recoil kinematics:

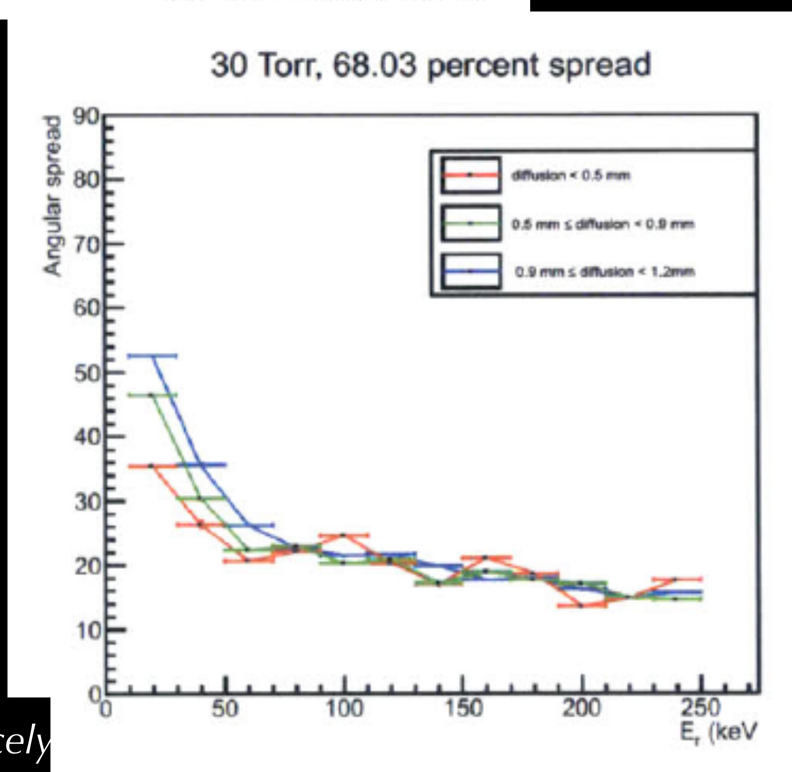


+ straggling:

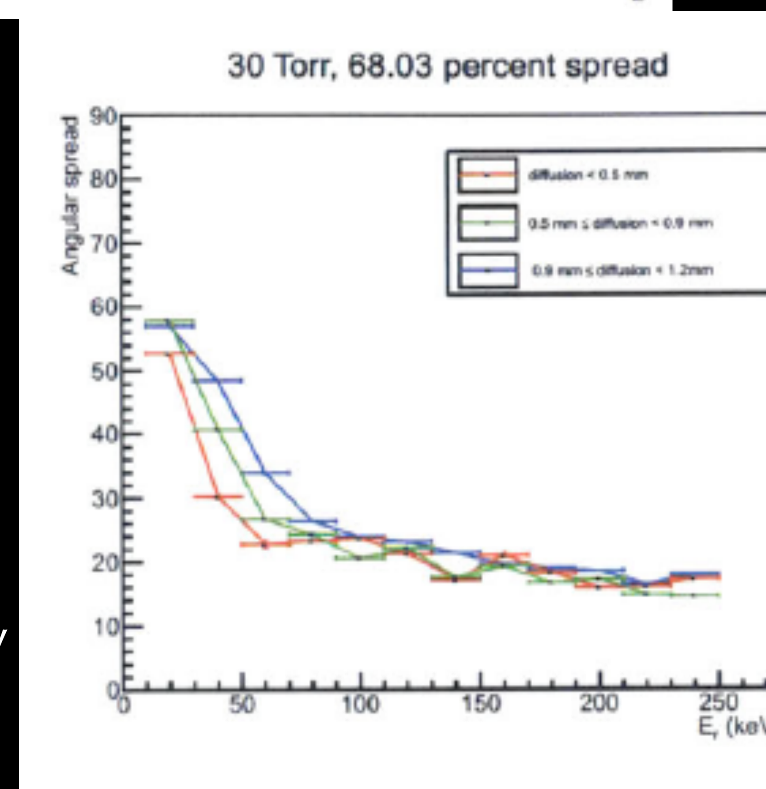
σθ of recoil direction, relative to initial track direction ~25° @ 50 keV



2) + diffusion: **σθ** ~30° @ 50 keV



3) + TPC gain and 500 um readout pitch **σθ** ~35° @ 50 keV

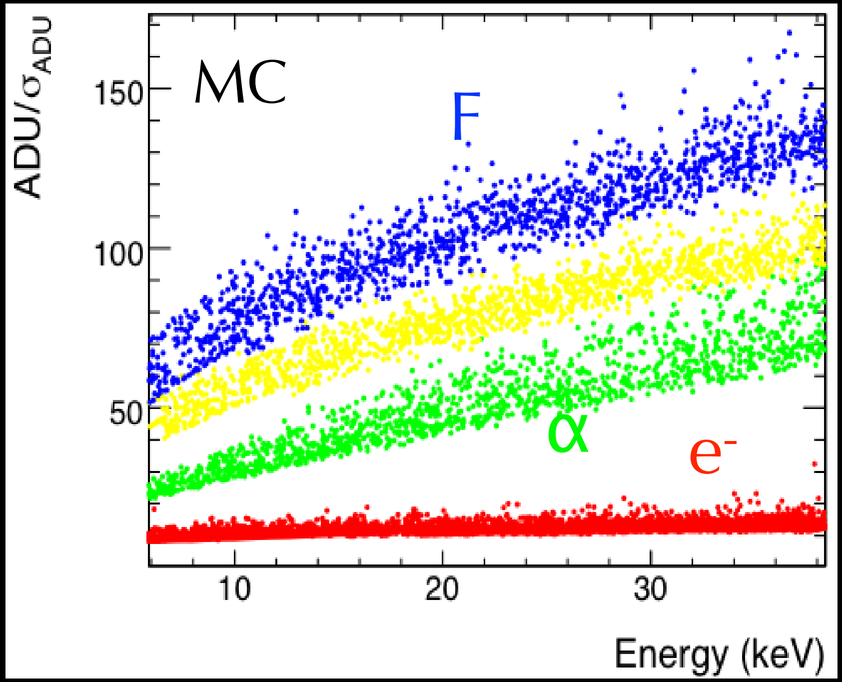


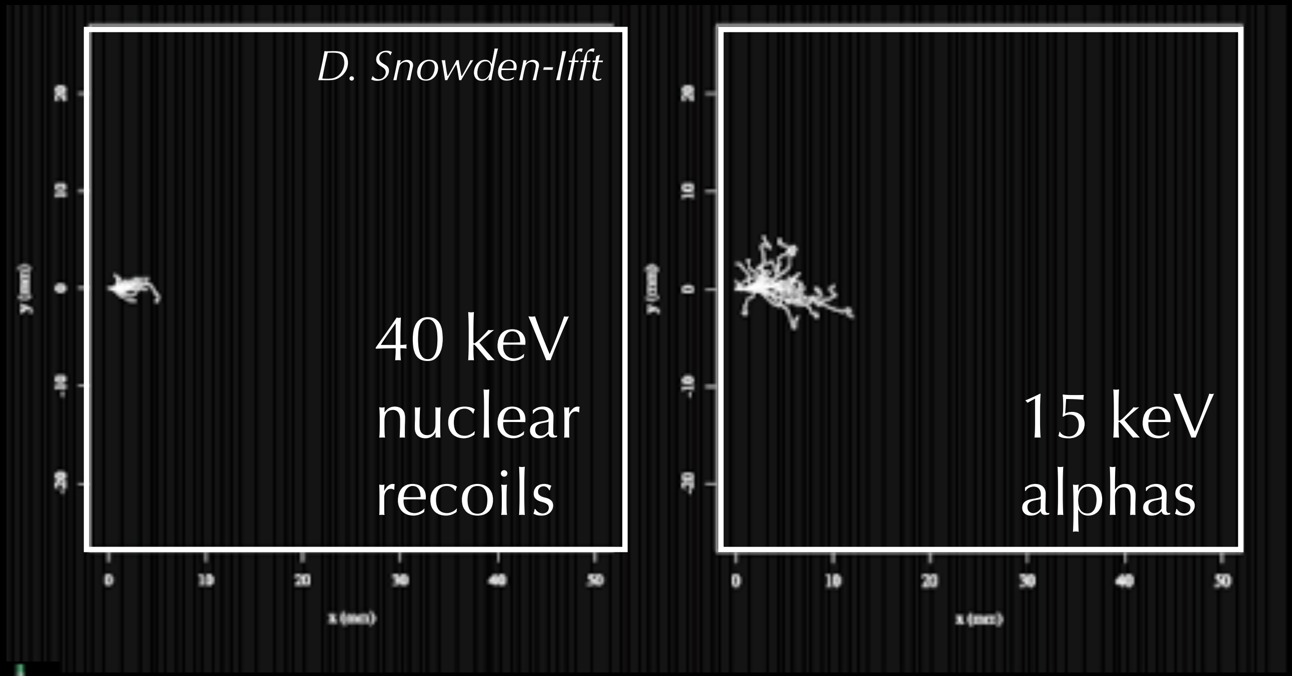
Backgrounds in Directional Detectors

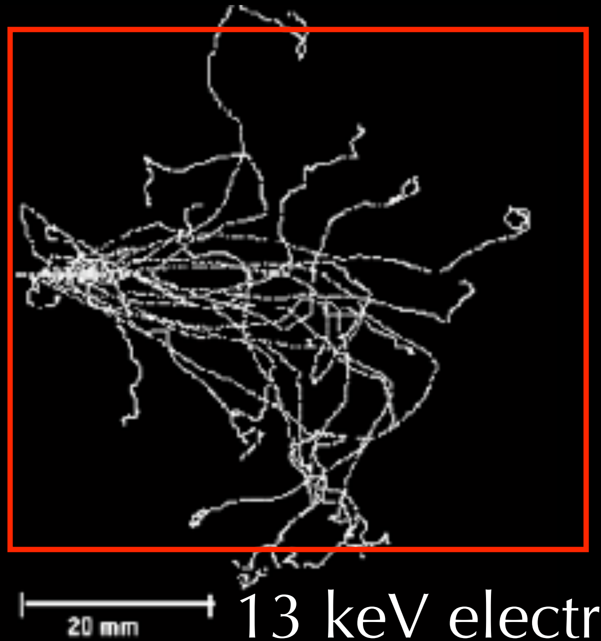
Three strategies:

1. range vs. energy
2. tracking (10^6 electron rejection)
3. angular distribution
   (important for ν-N coherent scattering!)

JM, P. Fisher, Phys. Rev. D 76:033007 (2007)

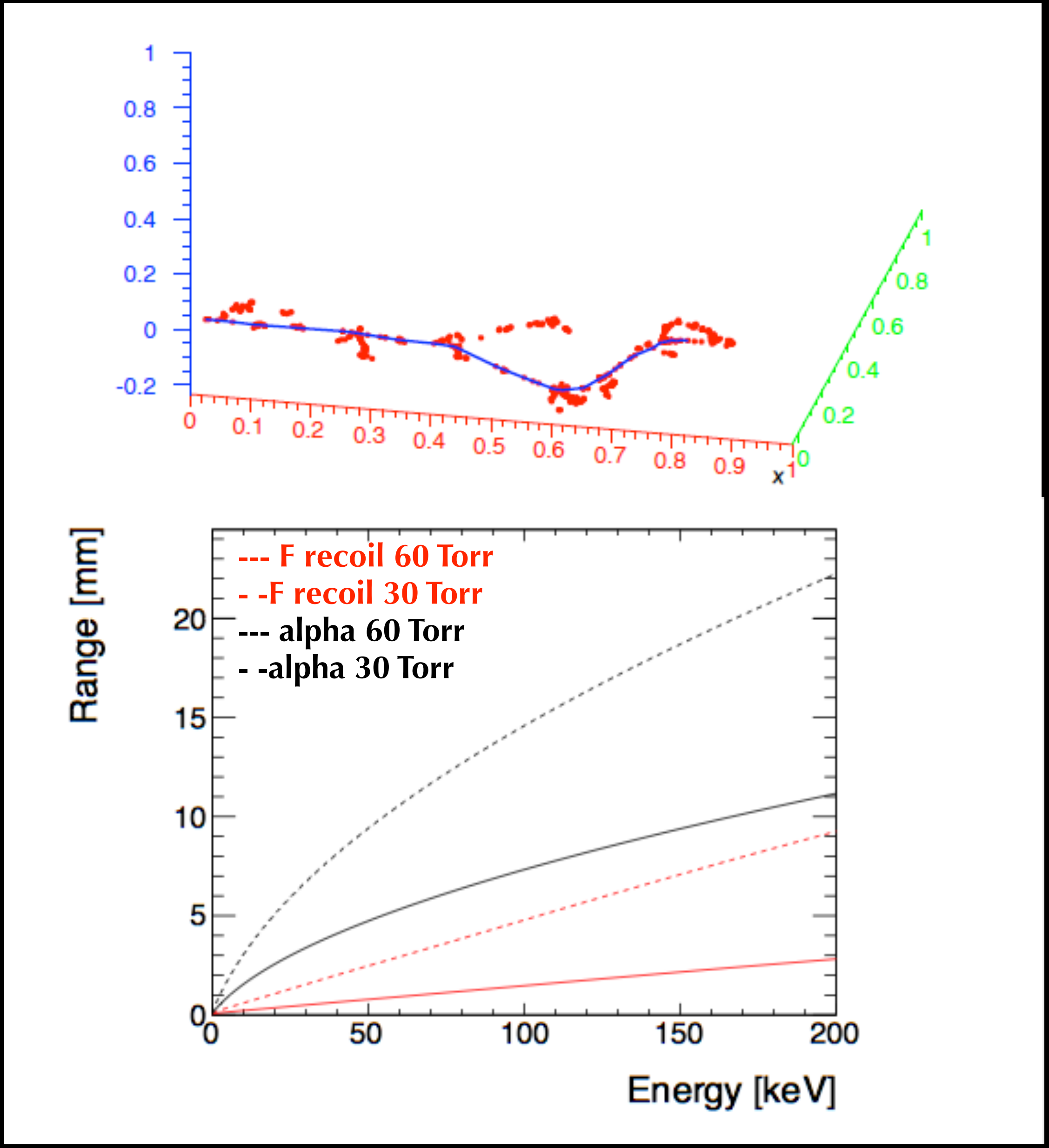






13 keV electrons

Readout Requirements: Segmentation and Low Noise



At 50 keV, F recoil track length is 1 mm (@ 60 Torr CF4), 2.5 mm (@ 30 Torr CF4).

As the F travels, it loses energy to the medium, which has significant fluctuations (straggling)

To determine the track angle requires > 2 measurements along the track, and in the presence of straggling, readout noise, etc. require more.

need >500 um resolution, for direction measurement at 50 keV recoil energy.

given quenching and W for CF_4, primary signal size of $O(10^2 - 10^3)$ e- / track

Timeline of Optical TPCs (using CCDs)

1988 Masek et al., da… 1988: CCD cost (my estimate) 0.05$/channel …CD in
P-10/CH_4 + TEA, MWPC + 4.5 kG B field *PRL73 8 (1994) 1087*

1988 Charpak, Breskin et al., UV RICH, multi-stage MWPC + intensifier + CCD
Nucl. Instrum. Methods A 273 (1988) 798, IEEE Trans.Nucl.Sci. 35 (1988) 483-486

2002 Fraga et al., thermal neutron imaging with CCD readout of GEMs
Nucl. Instrum. Methods A 478 (2002) 357

2006 Weissman et al., (O-TPC) nuclear astrophysics cross sections with multi-stage MWPC + image intensifier + CCD in CO2 (80%) + N2 (20%) mixtures
J. Instrum. 1 (2006) P05002

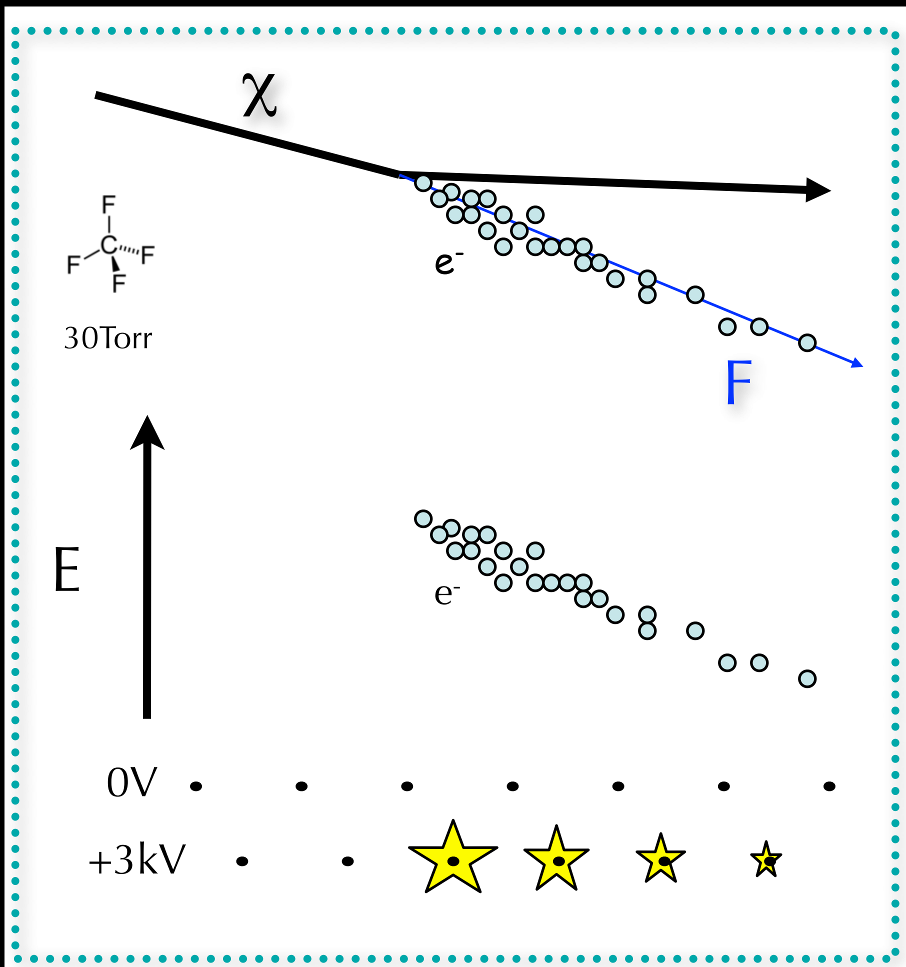
2007 Dujmic et al., (DMTPC) dark matter directional detection, with mesh-based amplification region + optical lens + CCD, in CF_4 mixtures
Nucl.Instrum.Meth. A584 (2008) 327-333

2014 Phan et al., dark matter directional detection, GEMs + CCD in SF_6
Physics Reports 662 (2016) 1-46

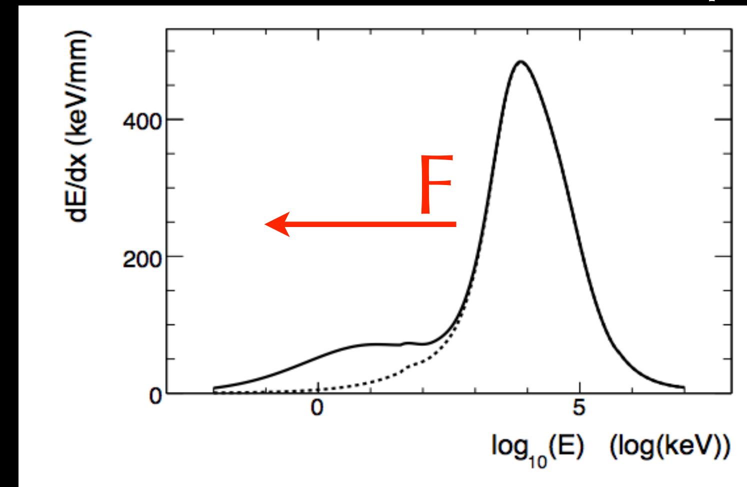
2016 CERN GDD (Reindl, Resnati et al.), MPGDs + CCD studies with RD51
https://indico.cern.ch/event/568177/

2016: CCD cost (my estimate) 0.005$/channel)

Dark Matter Time Projection Chamber (DMTPC) Principle



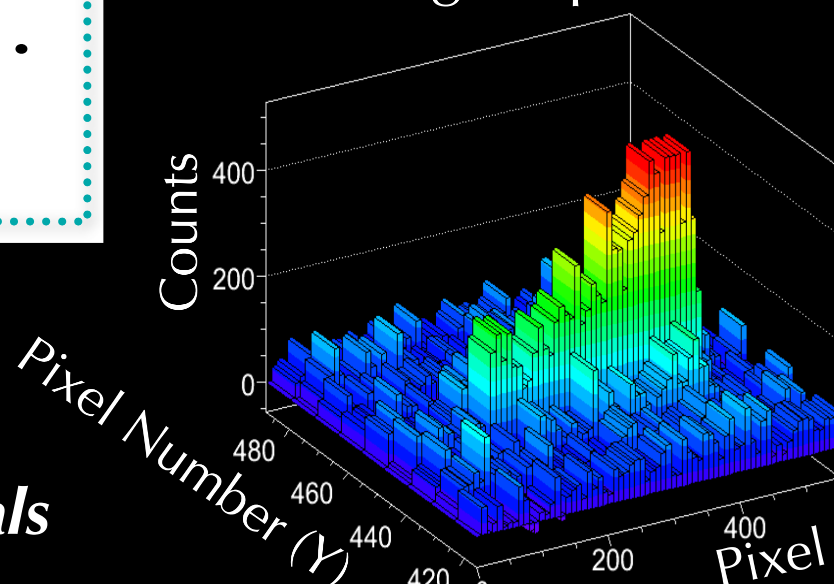
1. primary ionization encodes track direction via dE/dx profile



2. drifting electrons preserve dE/dx profile if diffusion is small
3. multiplication in amplification region produces e- + scintillation

0.005$/ channel

minimum wetted materials

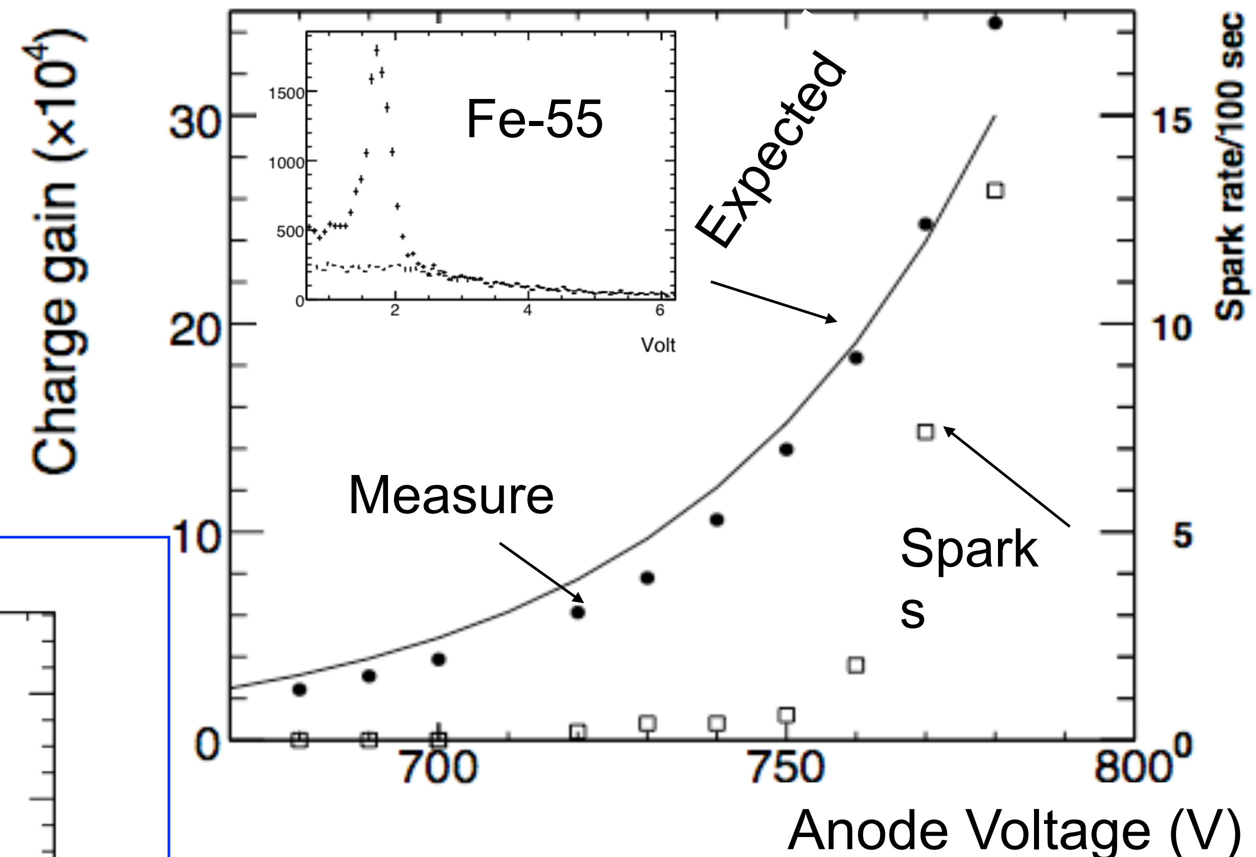


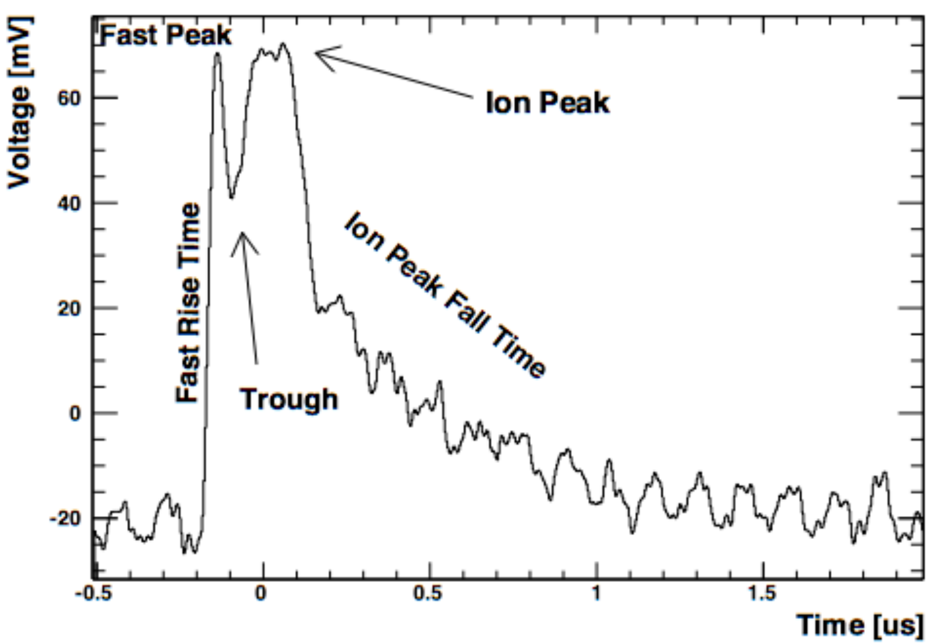
D. Dujmic, JM et al., NIM A 528 (2008) 327

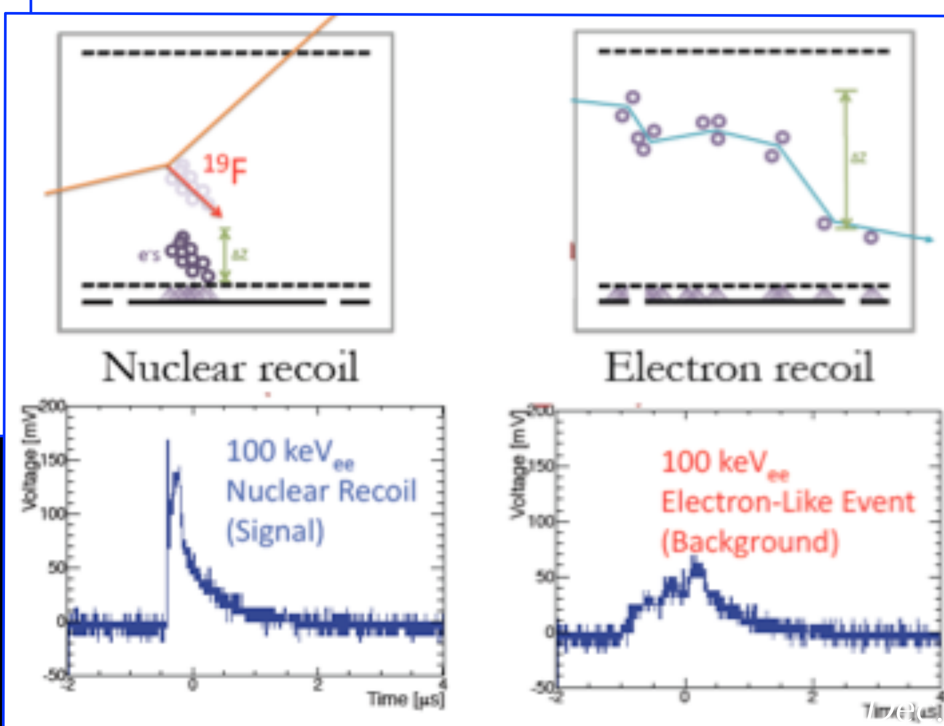
Charge Readout

Multiplication calibrated with Fe-55, anode signal amplitude

$M \sim (V_{out} x 1.4 pC/V) / (5.9 keV/W)$
W = 33.8 +/- 0.4 eV *(I. Wolfe S.B.thesis*



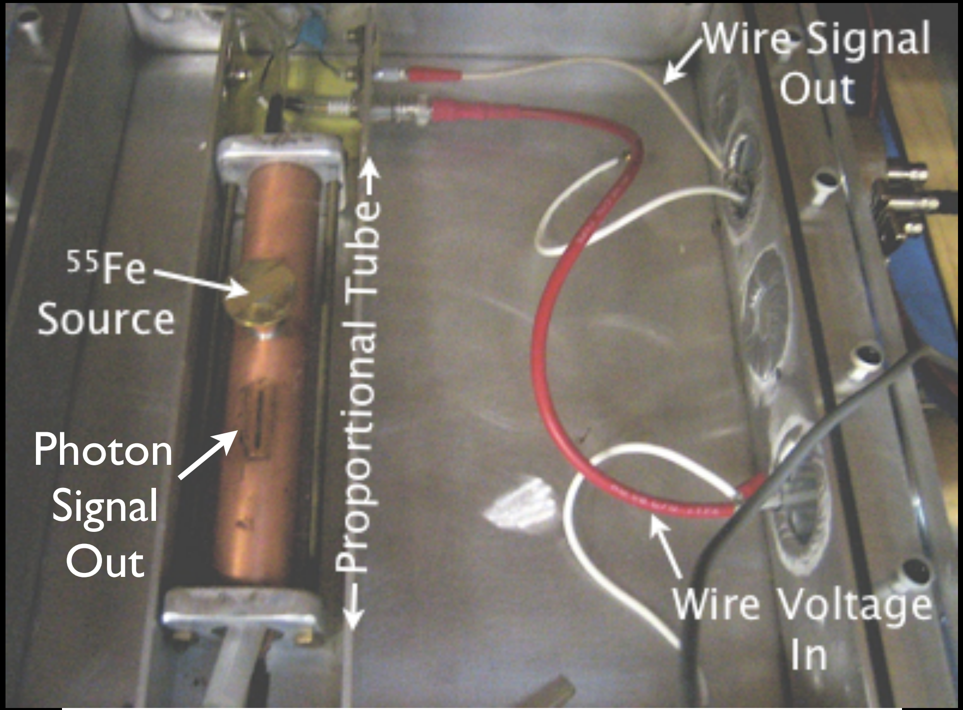




Mesh signal readout with ns-risetime amplifier, to measure Δz and for PID

CF_4 Scintillation

ratio of scintillation to ionization in avalanche determines optical 'gain'

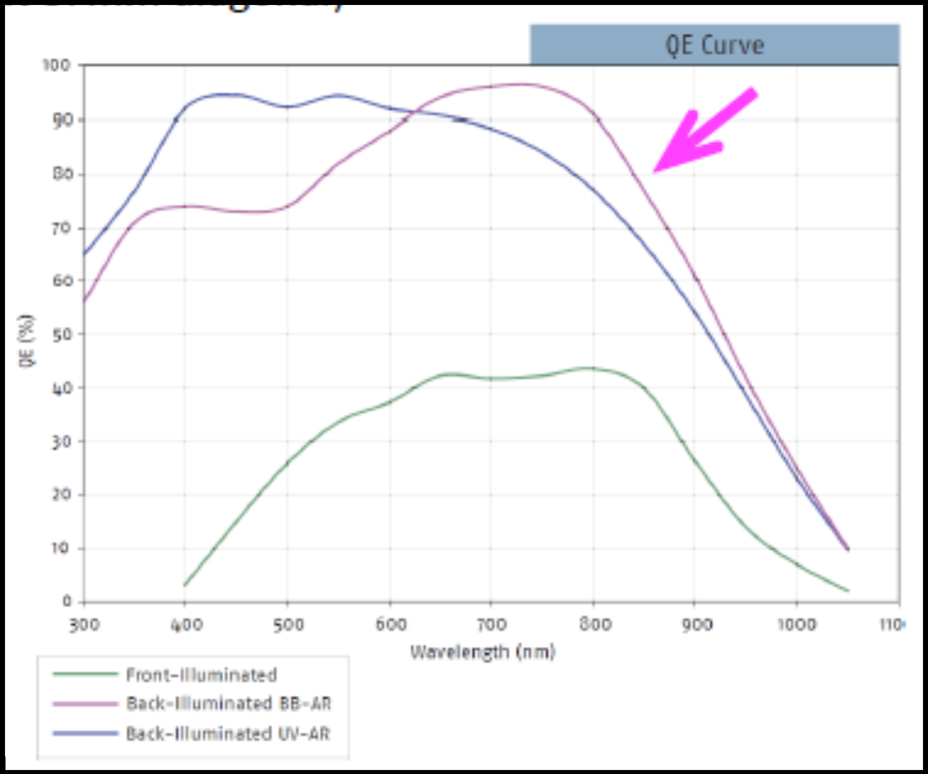


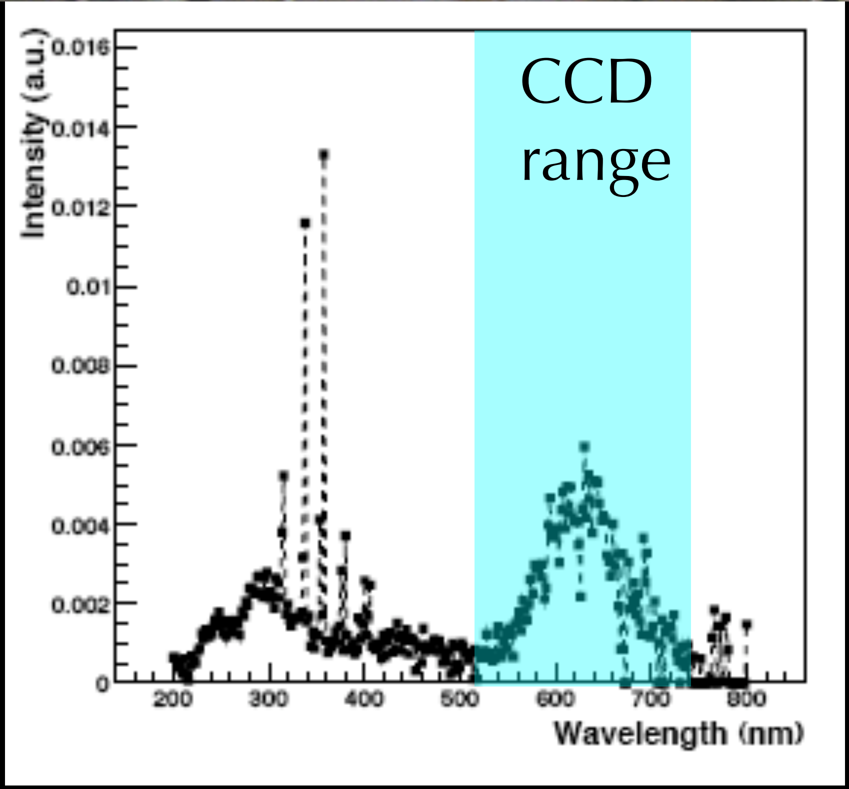
measurement 140-180 Torr,

result: γ/e^- *= 0.34 +/- 0.04*

A. Kaboth, JM, et al., NIM A 592:63-72 (2008)

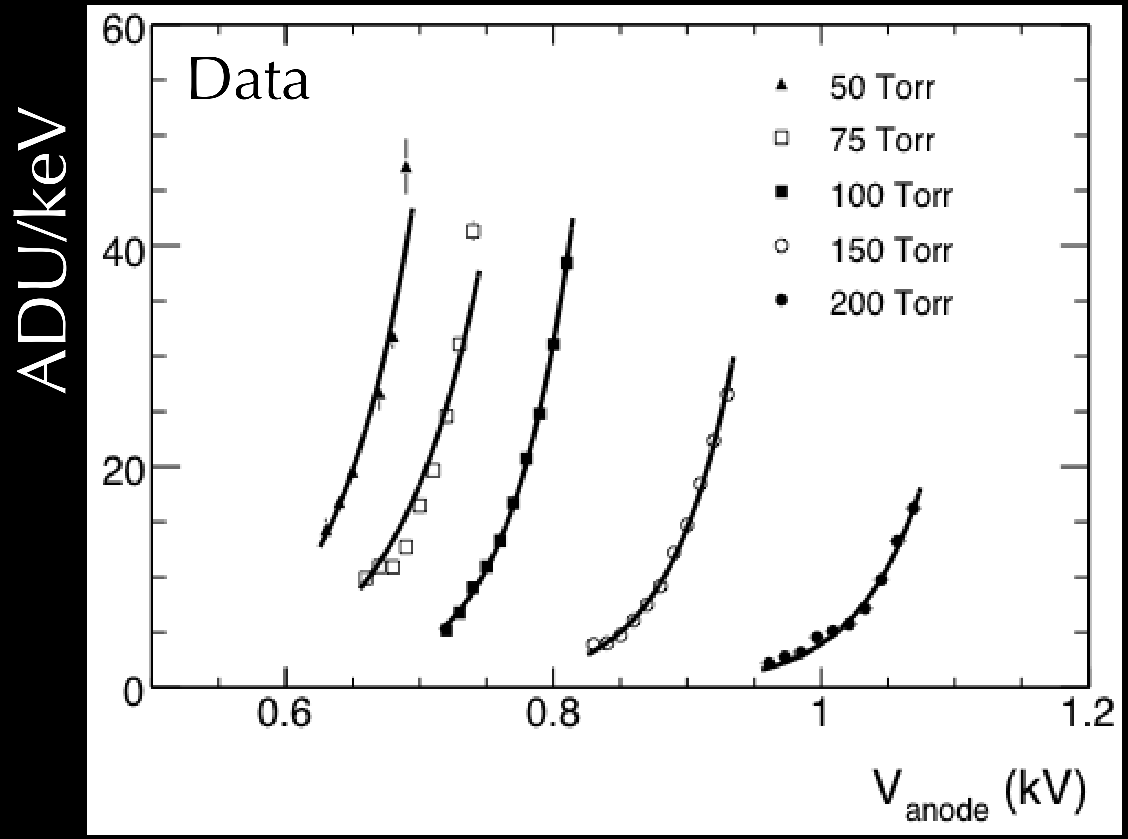
CF_4 spectrum well-matched to CCD QE





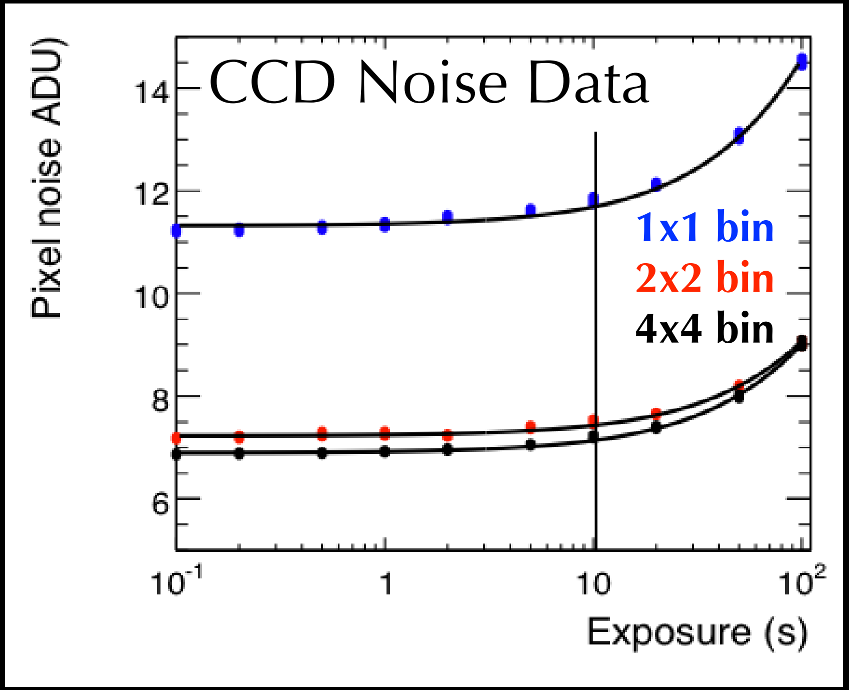
CCD Readout

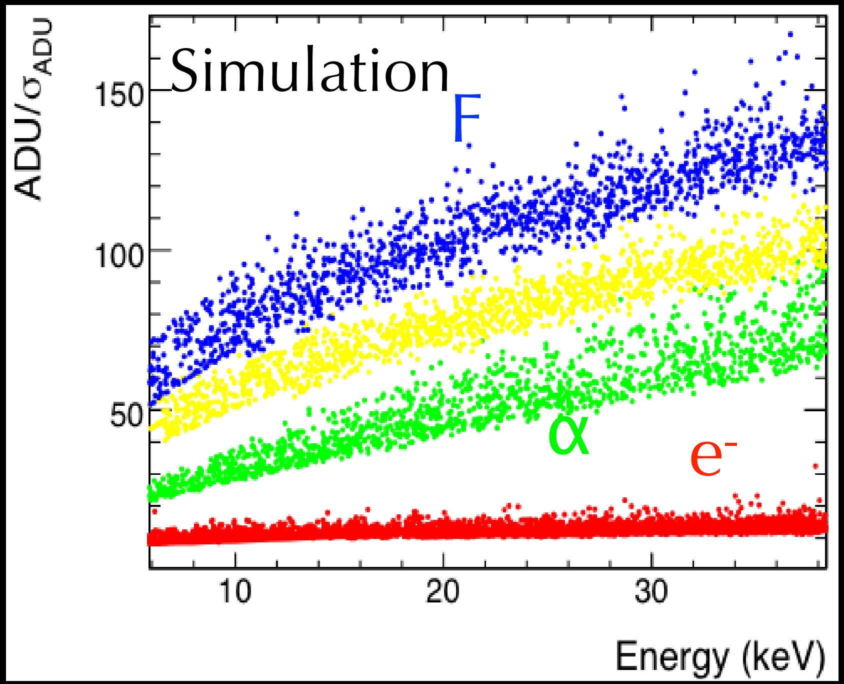
Total optical system gain:



Increasing gain + track length with lower pressure, but decreasing mass!

Key to identifying low energy tracks is S:N per pixel, @50 keVr want S:N >10

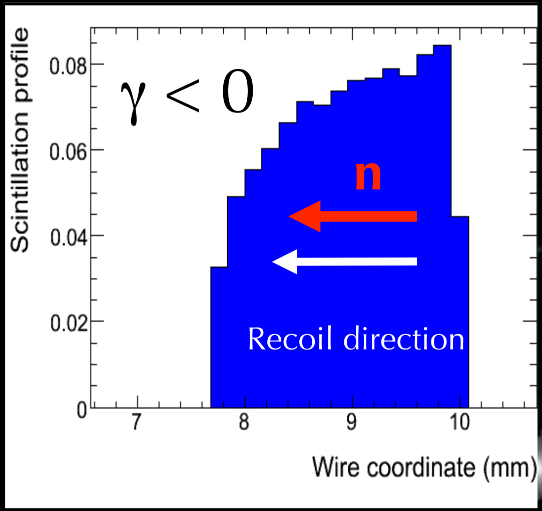


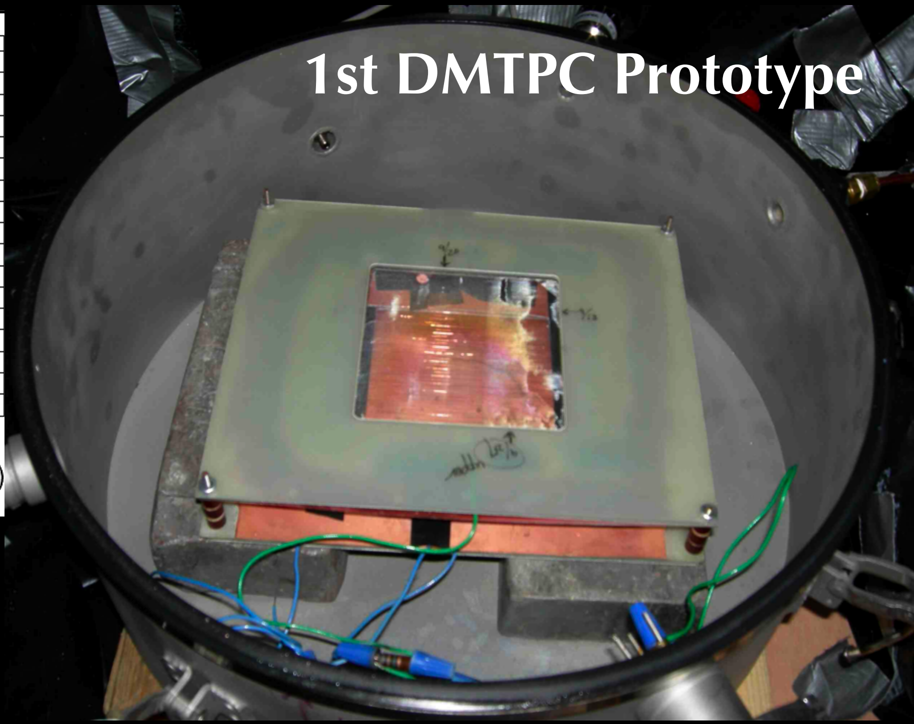


Directionality I

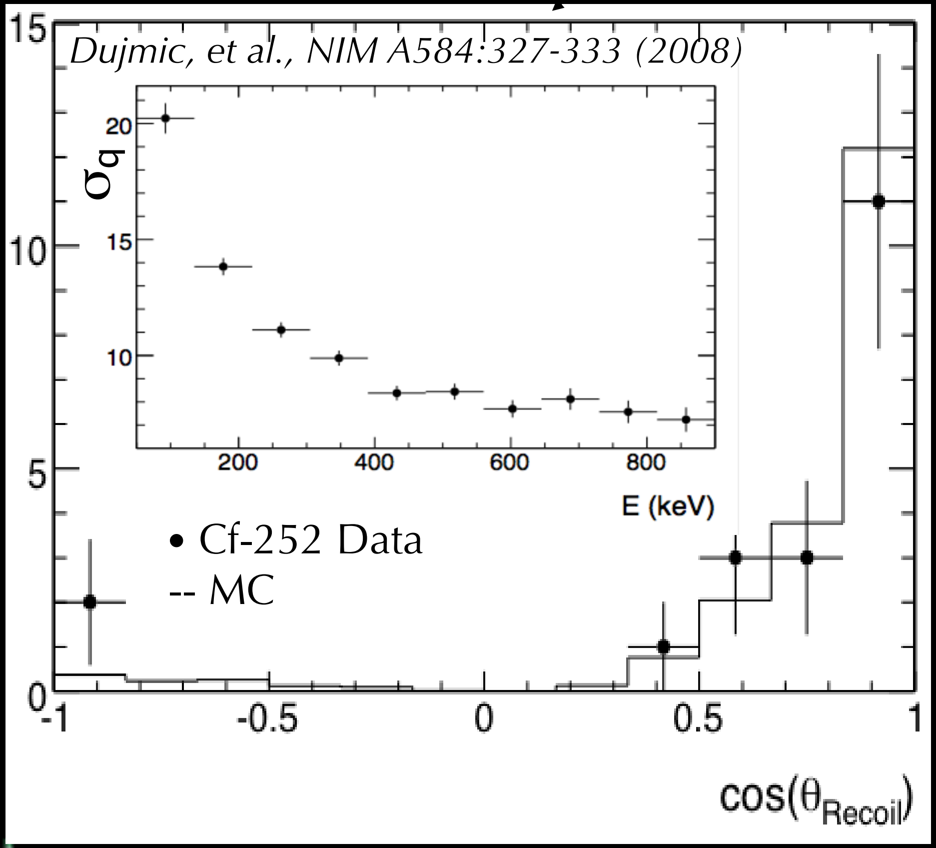
CCD readout of 100 torr TPC with MWPC

2D angle + head-tail from light asymmetry (measure skewness)



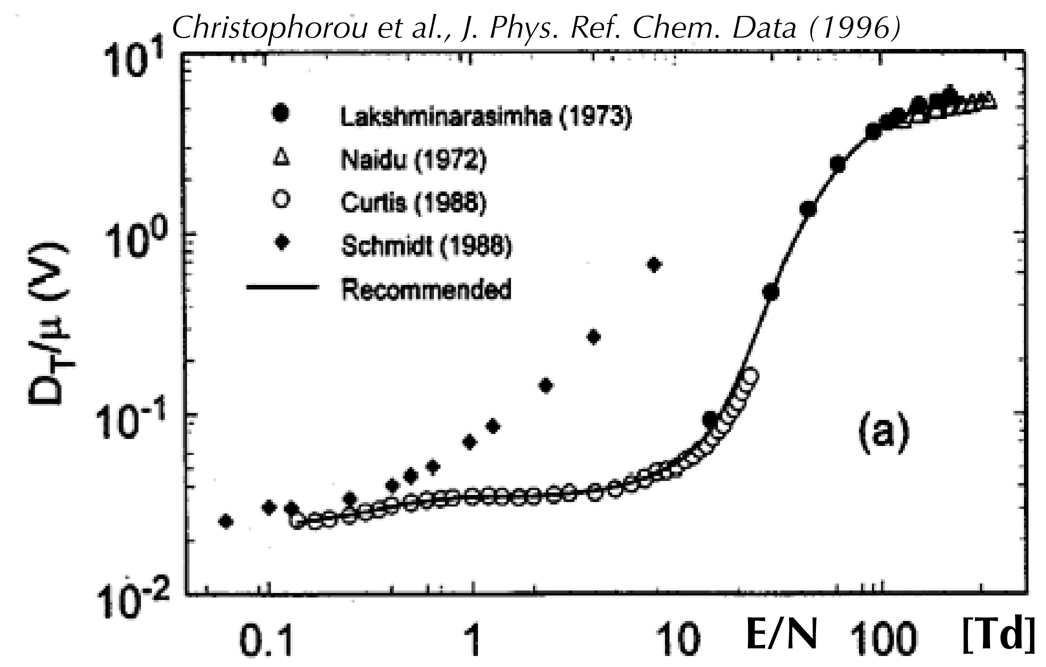


Signed cosine (E>200 keV), 5 cm drift

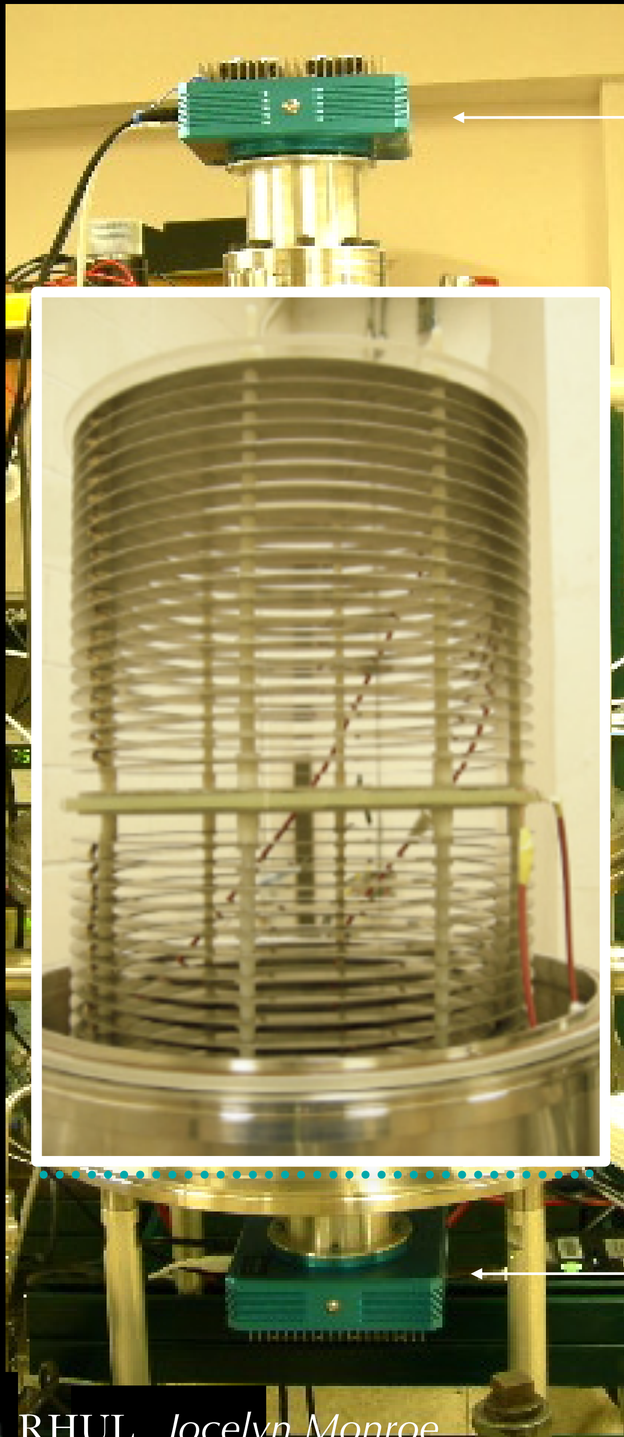


challenge to scaling up: diffusion!

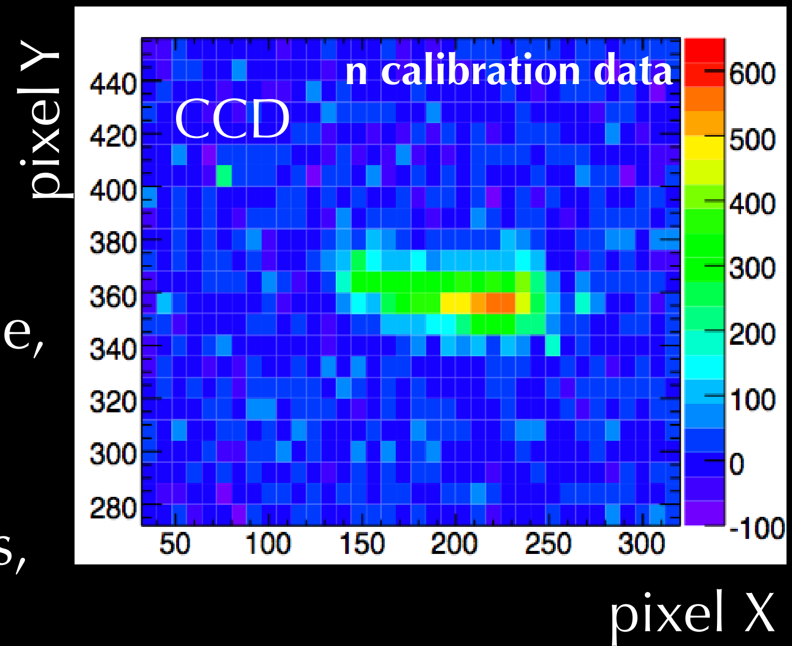
$$\sigma^2 = (D/\mu)\ 2\ z_{DRIFT} / E$$

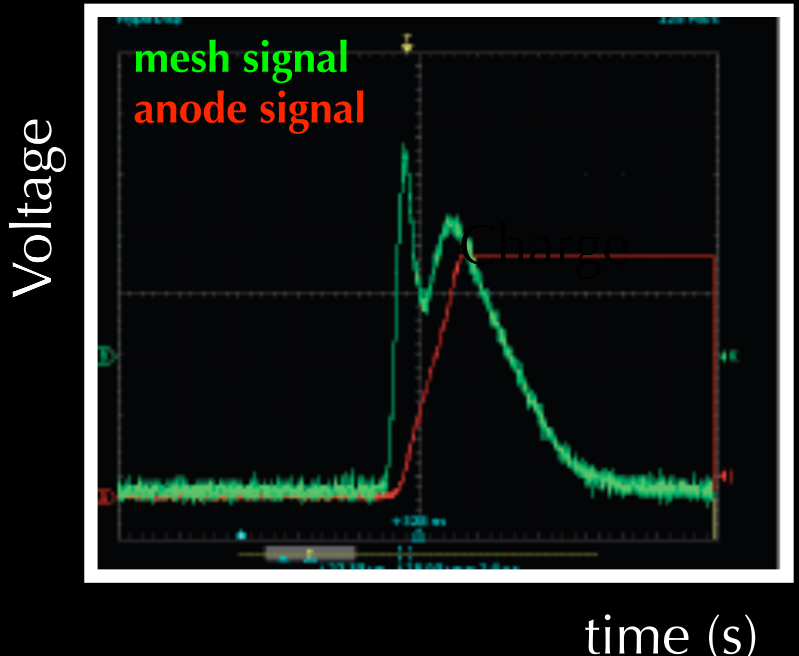


2nd Prototype



10L active volume,
20 cm drift,
CCD and charge readout of 2 TPCs,
75 torr CF_4

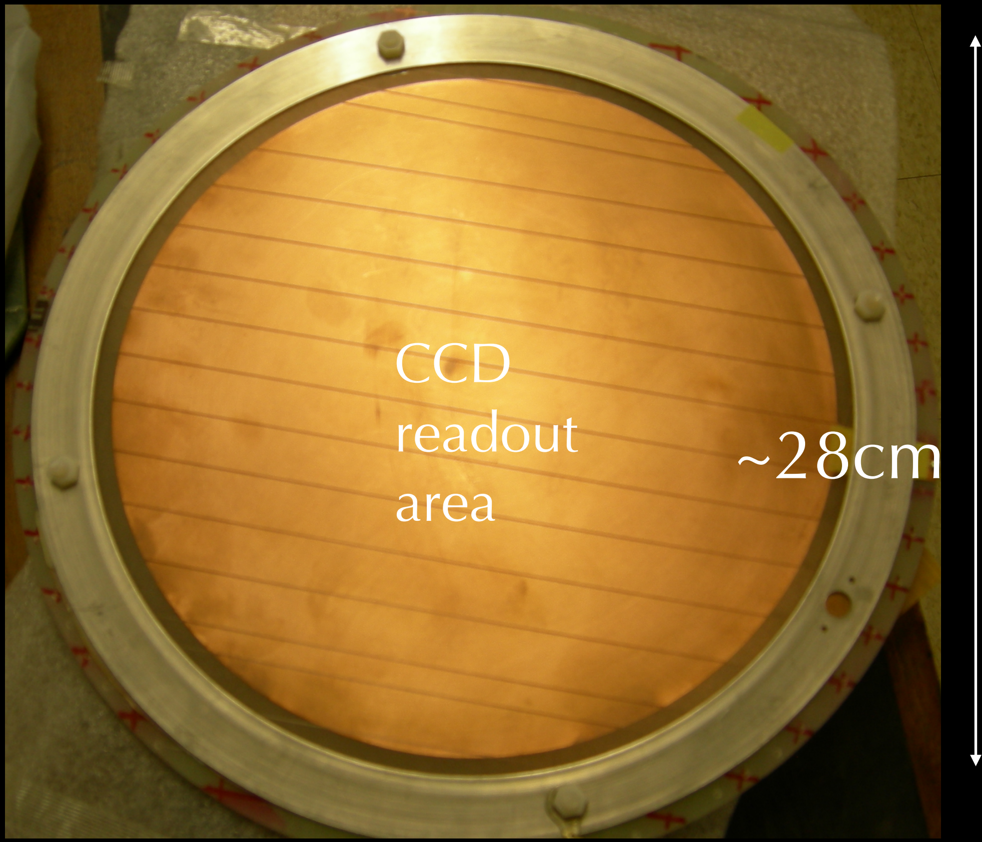




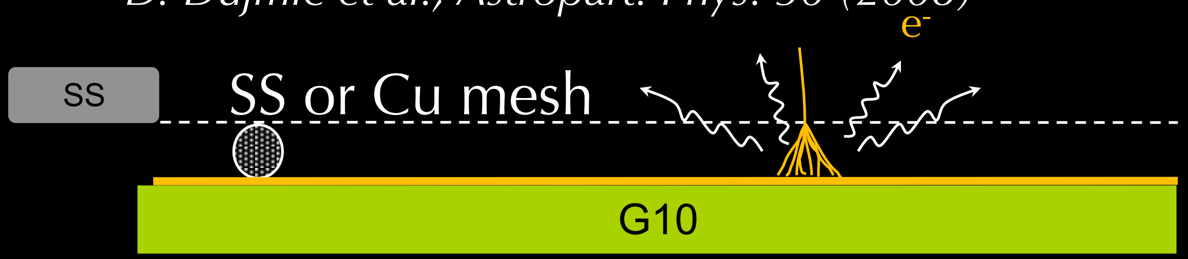
goal: charge and light = reject backgrounds + 3D R&D

Amplification Region

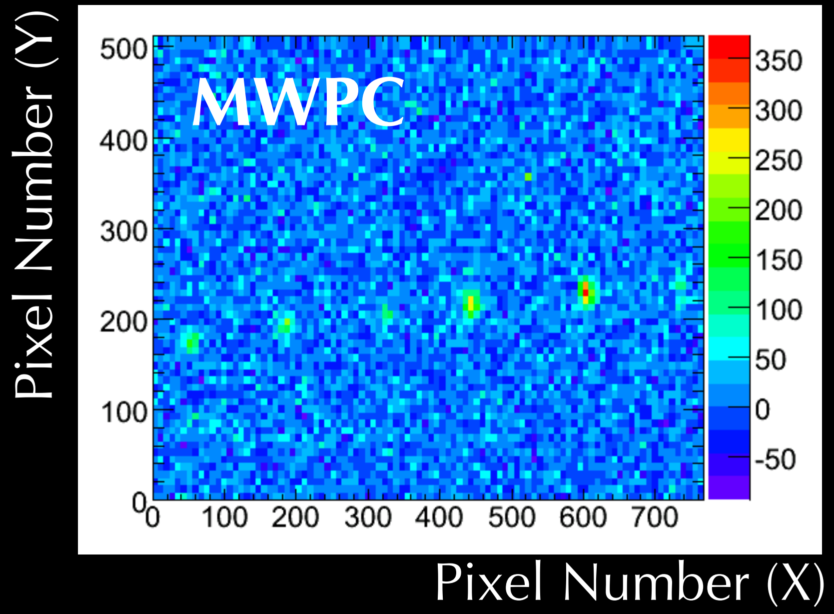
Cu Mesh, 256 um pitch

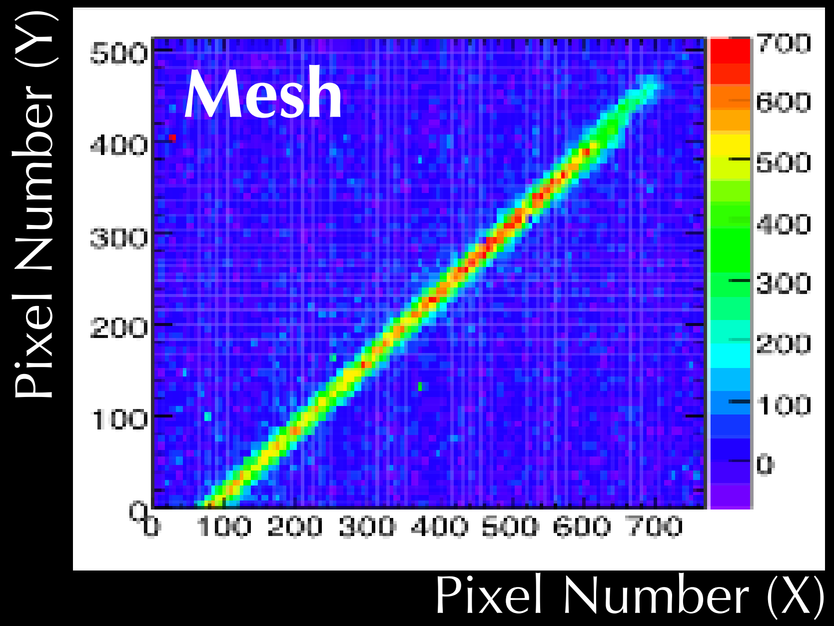


D. Dujmic et al., Astropart. Phys. 30 (2008)



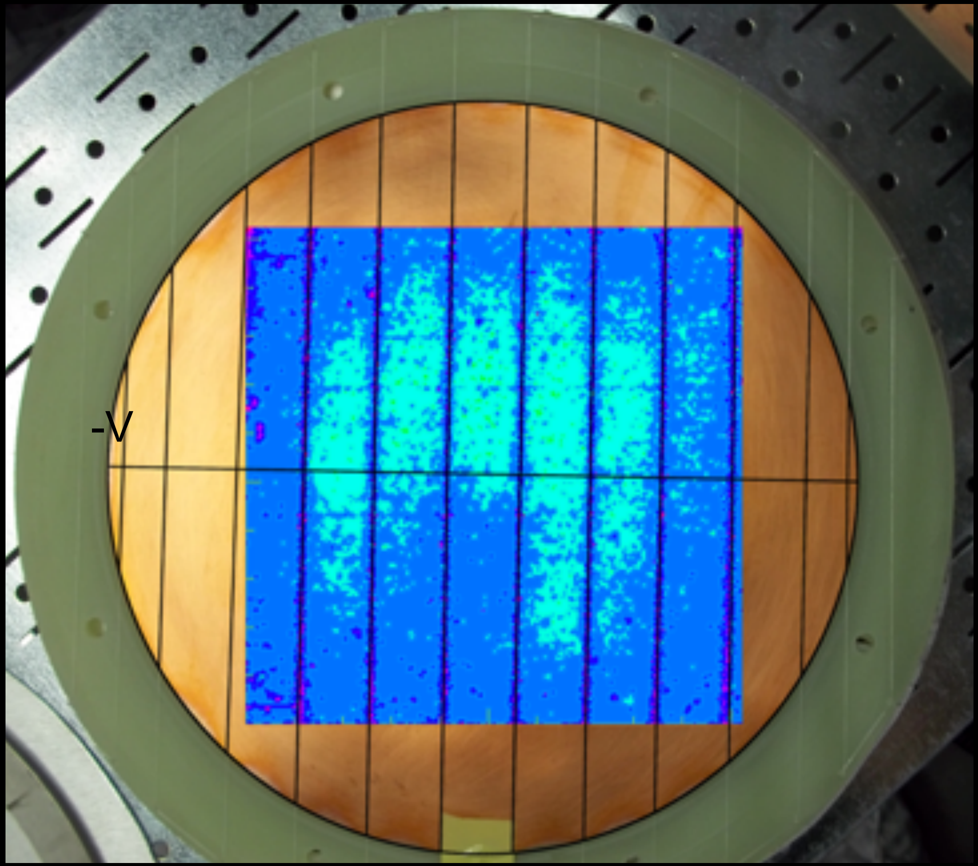
Resistive separators, dia=0.5mm, every 2.5cm





20x smaller pitch,
10x larger gain, 1->2D

CCD Length and Energy Calibration

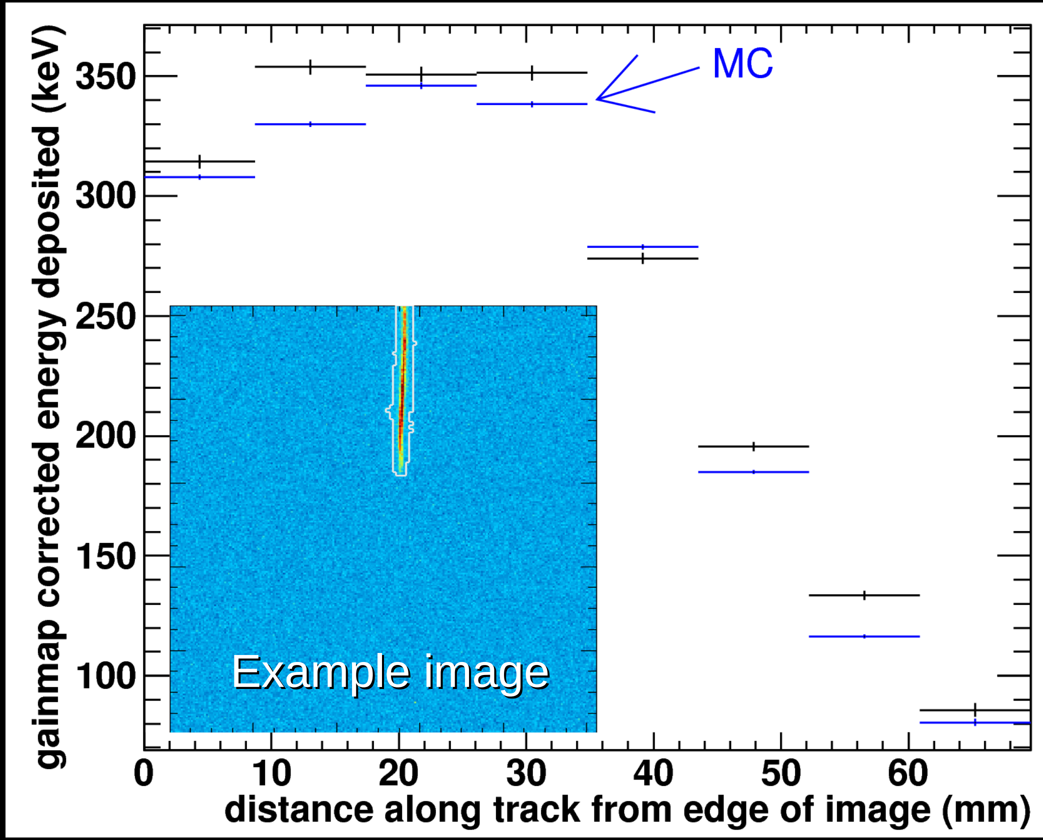


illuminate with Co-57 (122,137 keV) and Cs-137 (662 keV) for length calibration

measure optical plate scale by comparing features in gamma data with photo
typically ~140-170 um/pixel
(then bin 2x2 to 4x4 before readout)

α sources for energy calibration (4.4 MeV)

measure gain (ADU/keVee) by comparing **α** energy measured in external solid state detector with energy in CCD, at track end:
typical gain ~ 20-40 ADU/keV

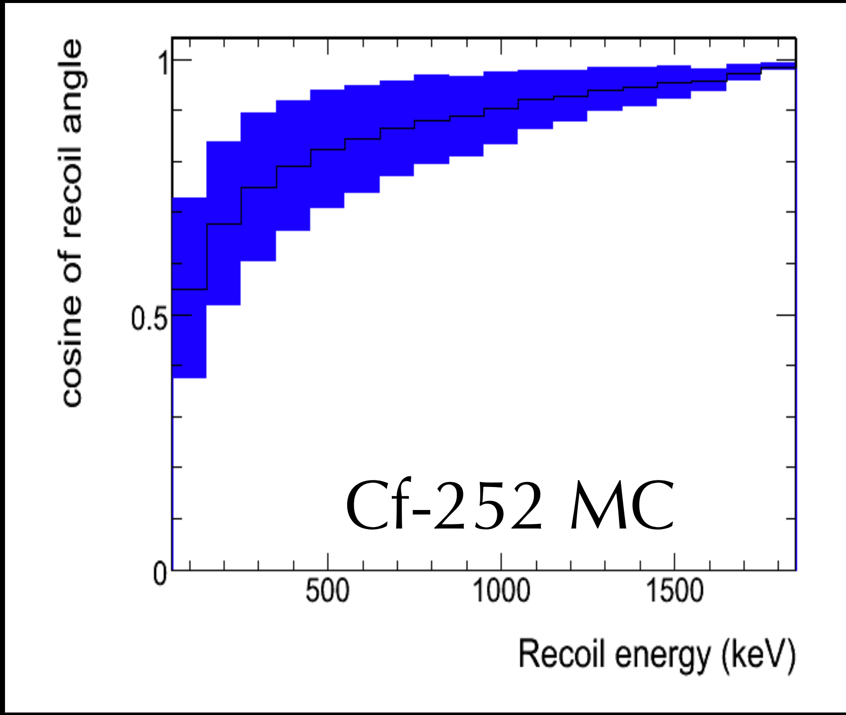


"WIMP" Calibration

Neutron elastic scattering mimics dark matter recoils, and most neutrons below ~4 MeV (n,alpha) production threshold

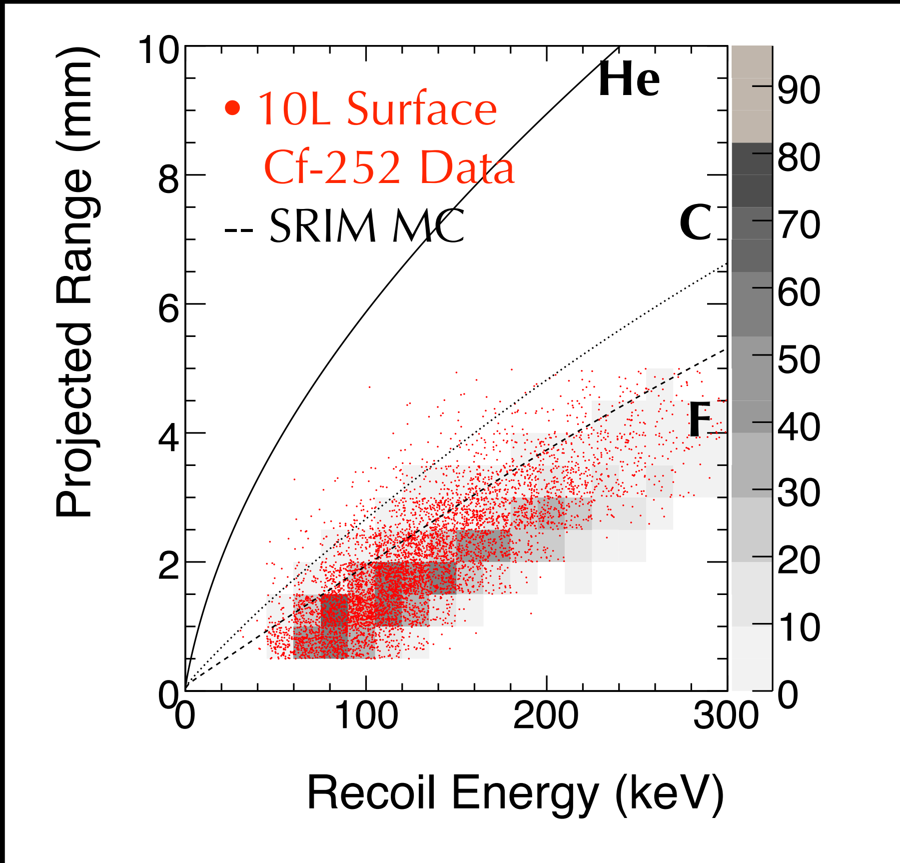
Cf-252 (~mCi), AmBe, and d-t n at surface, AmBe (8.9 uCi) source underground

100keV recoil angle	
Source	**Recoil angle**
14.1 MeV neutrons	80deg
Neutrons from AmBe	~68 deg (avg)
Neutrons from Cf252	~57deg (avg)
200GeV WIMP	~43deg (avg)



minimum recoil energy detected: 30-50 keV

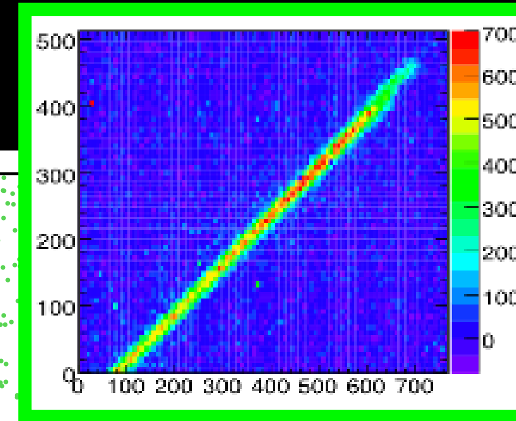
(Hitachi quenching model)

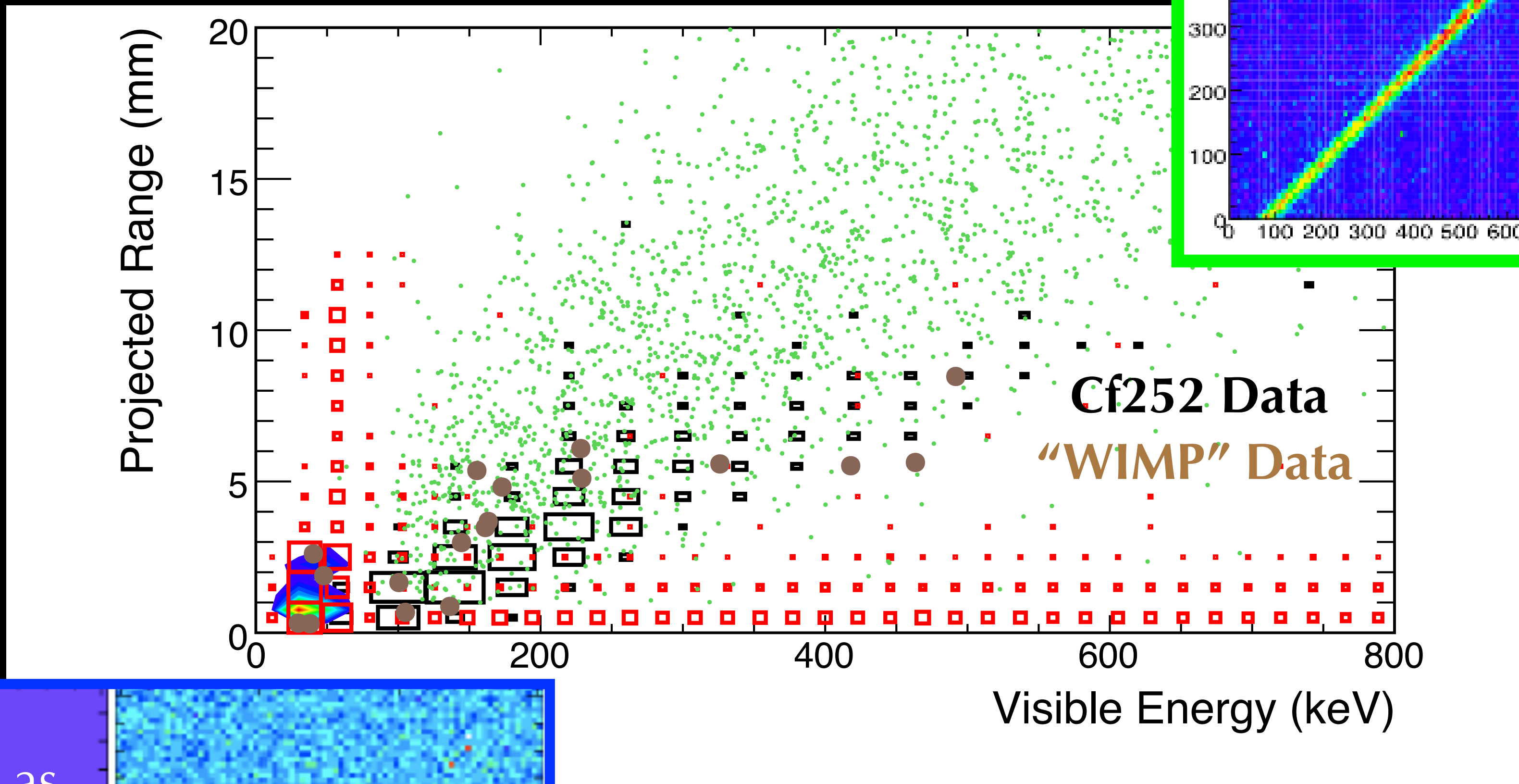


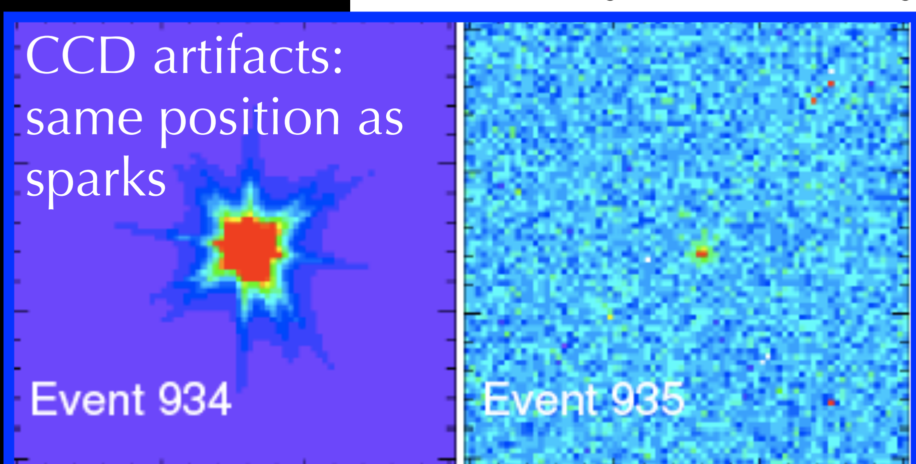
Energy and recoil angle distributions similar to dark matter induced recoils

Backgrounds, CCD Readout

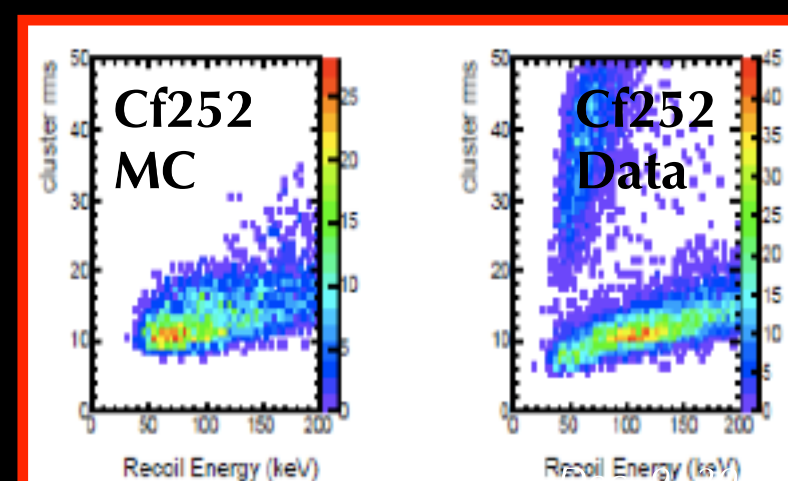
Alphas:
edge crossing







"Cosmics": one hot pixel, large cluster rms

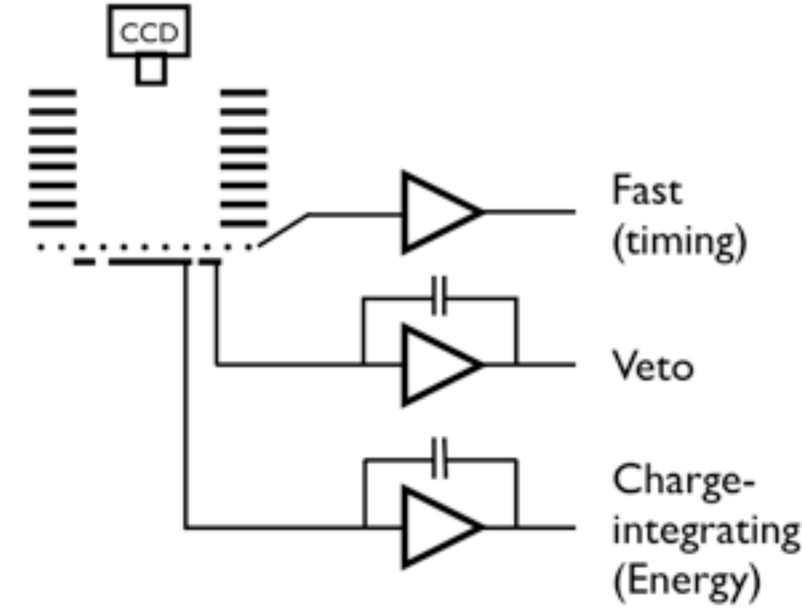


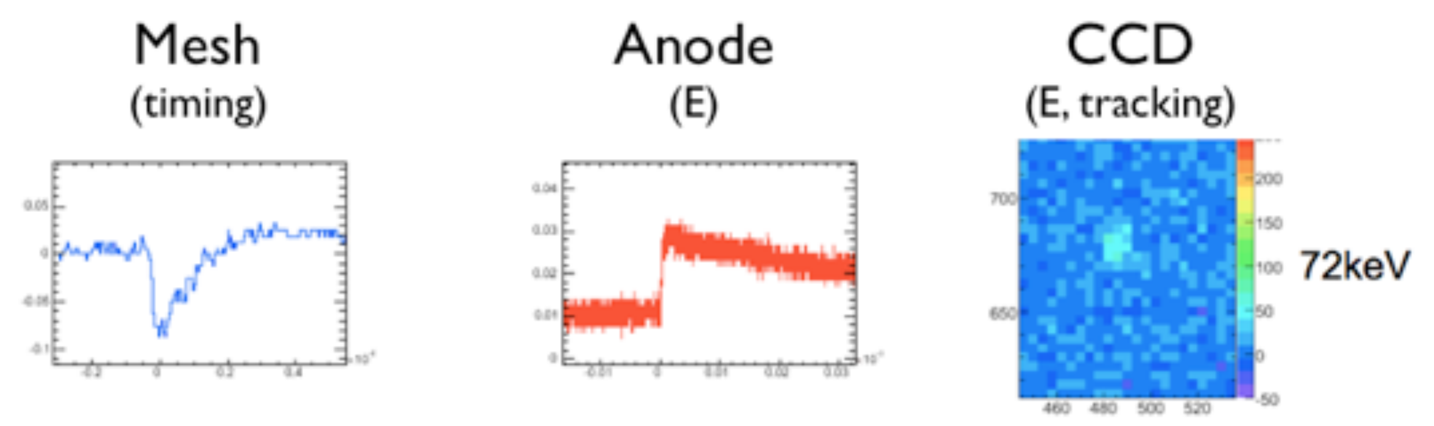
10^4 rejection of backgrounds from range vs. energy

S. Ahlen, et al., Phys. Lett. B 695 (2011)

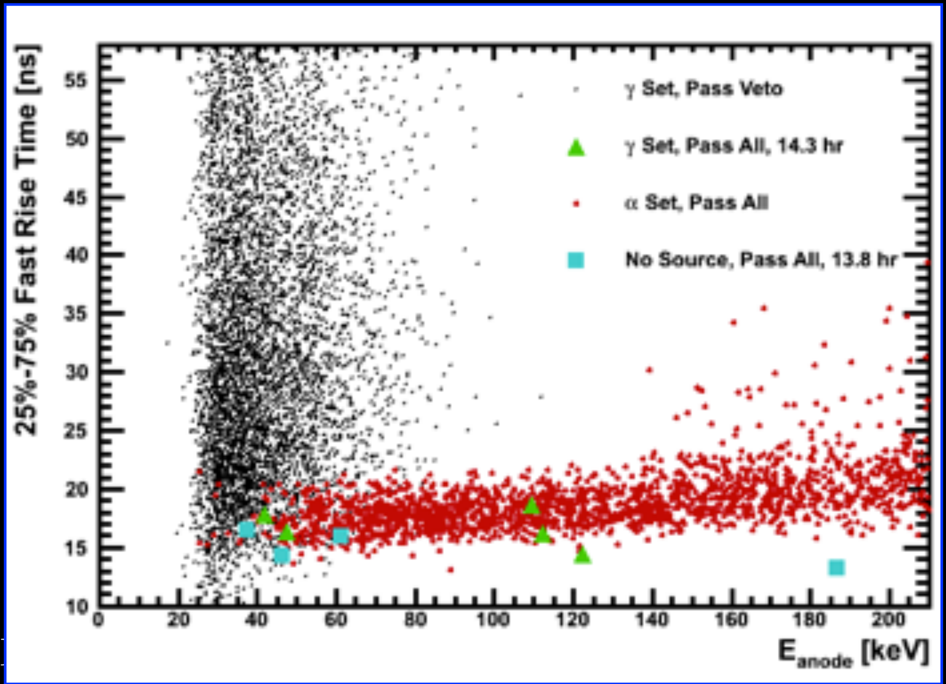
Background Rejection with Charge

optical AND charge readout rejects
CCD artifact AND gamma backgrounds
J. Lopez, JM, et al., NIM A 696 (2012) 121

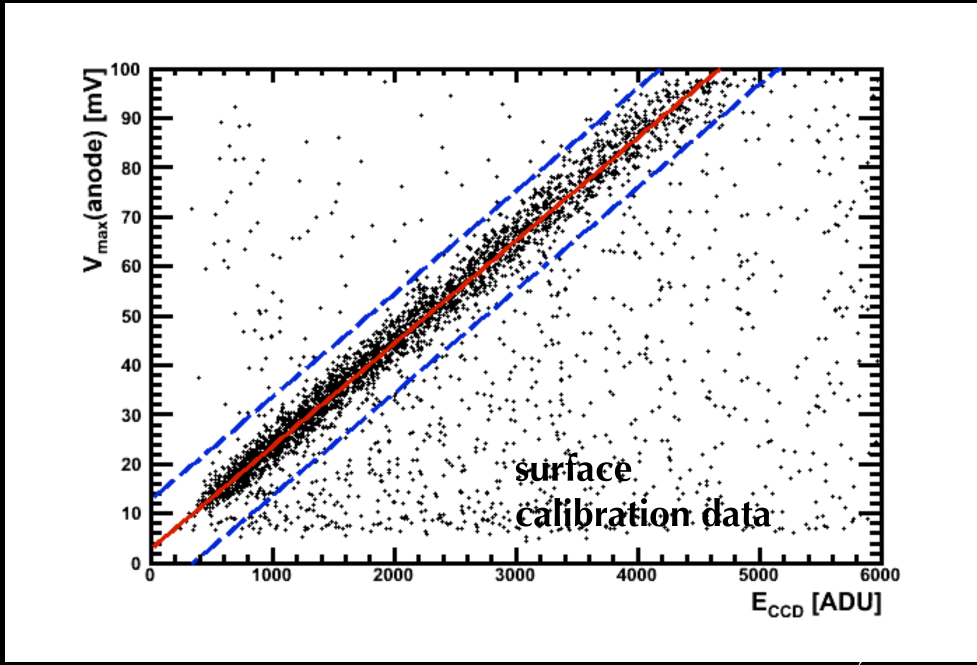




>1.1E-5 (90% CL) γ rejection from rise time vs. E:



~10^2 rejection from E_{charge} vs. E_{CCD}:



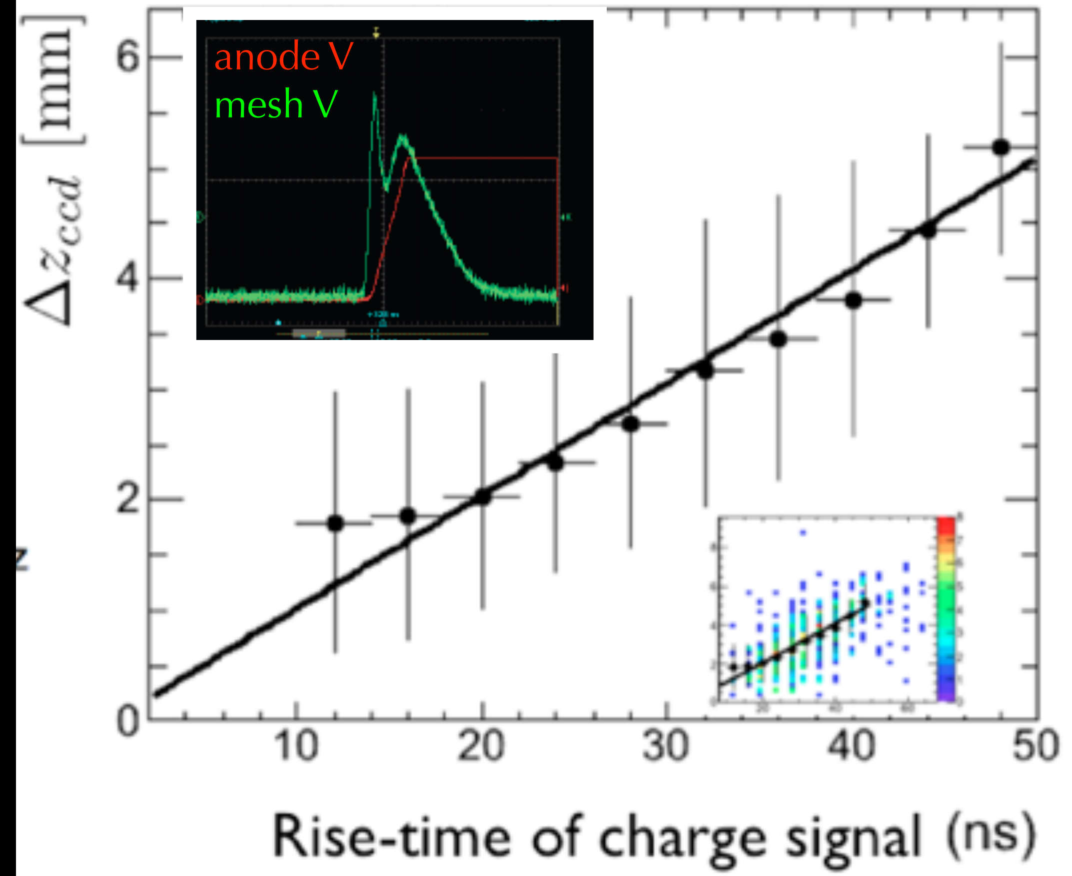
3D R&D

tracking in z (drift direction):

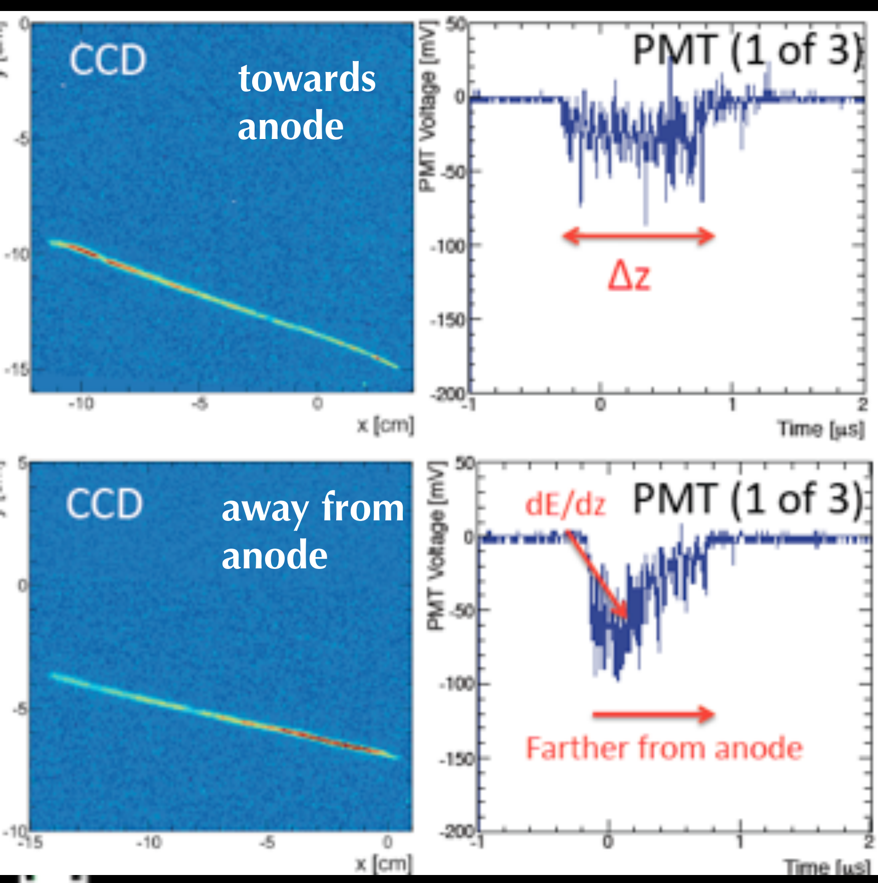
- angled alpha calibration source produces tracks of known Δz

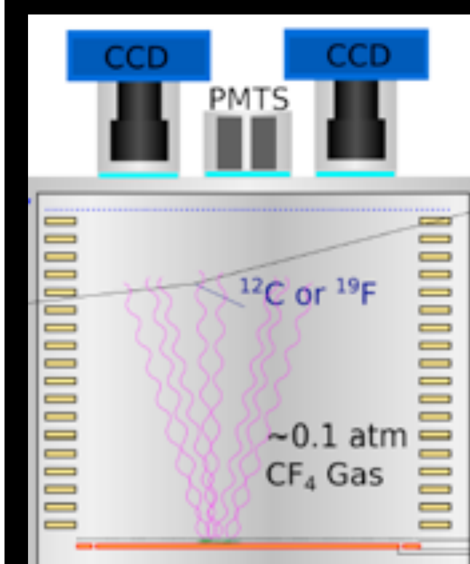
charge:

- measure mesh signal rise time
- find similar tracking resolution in Δz (from charge) as in x-y (from CCD)



J. Lopez, JM, et al., NIM A 696 (2012) 121





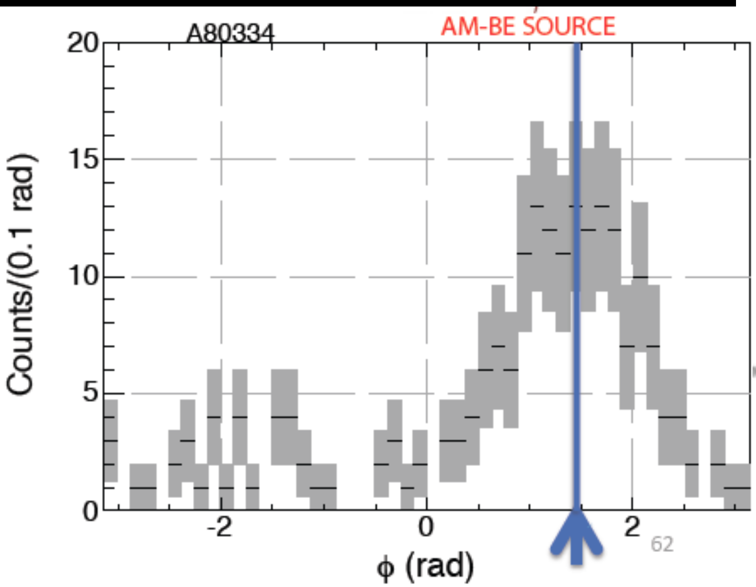
light:

- measure PMT signal pulse width
- pulse width varies with Δz, shape varies with +/-Δz

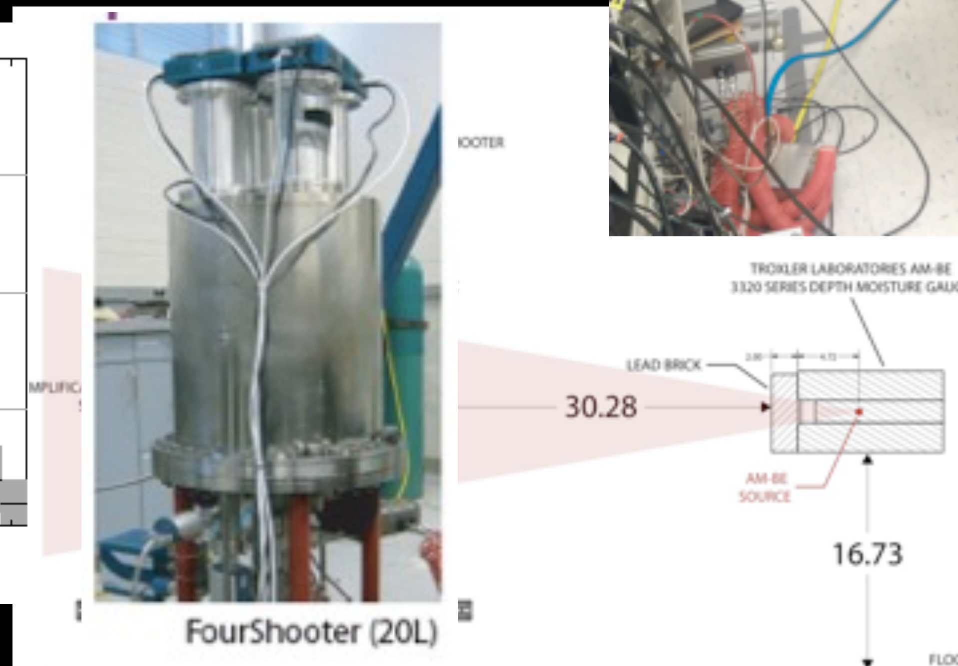
R&D on identifying cathode events using PMT readout

Direction Calibration

Need a source of known energy and angle

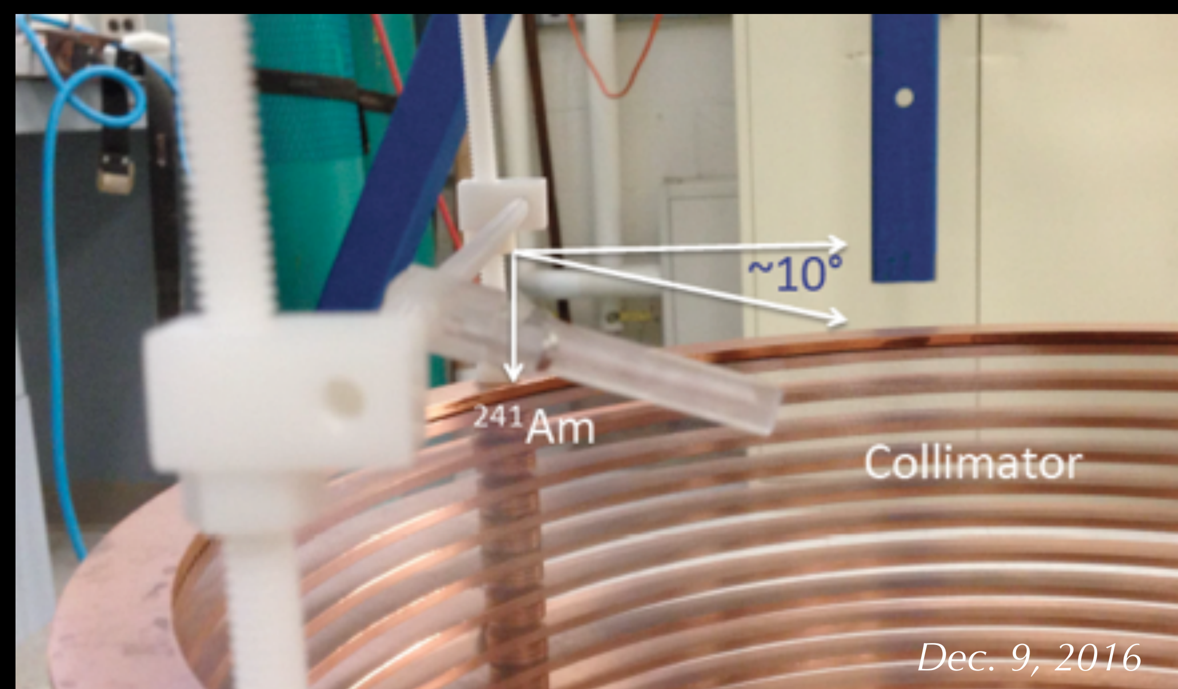


S. Henderson, PhD thesis (2013)



3rd prototype,
4 cameras,
25 cm drift,
20L active vol.

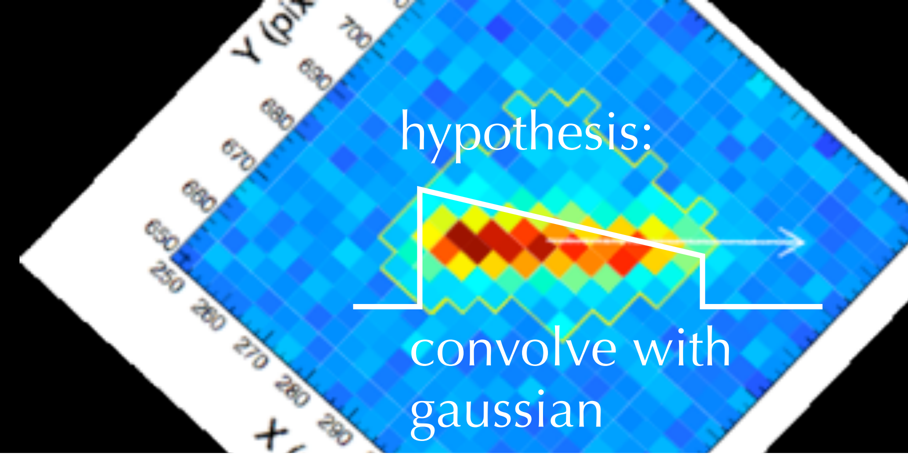
But, neutron scattering kinematics produce wide range of angles, and neutrons are hard to collimate.



Angled alpha calibration:

- only track ends in active region, can tune energy ~100 keVee
- tune angle by rotating collimator

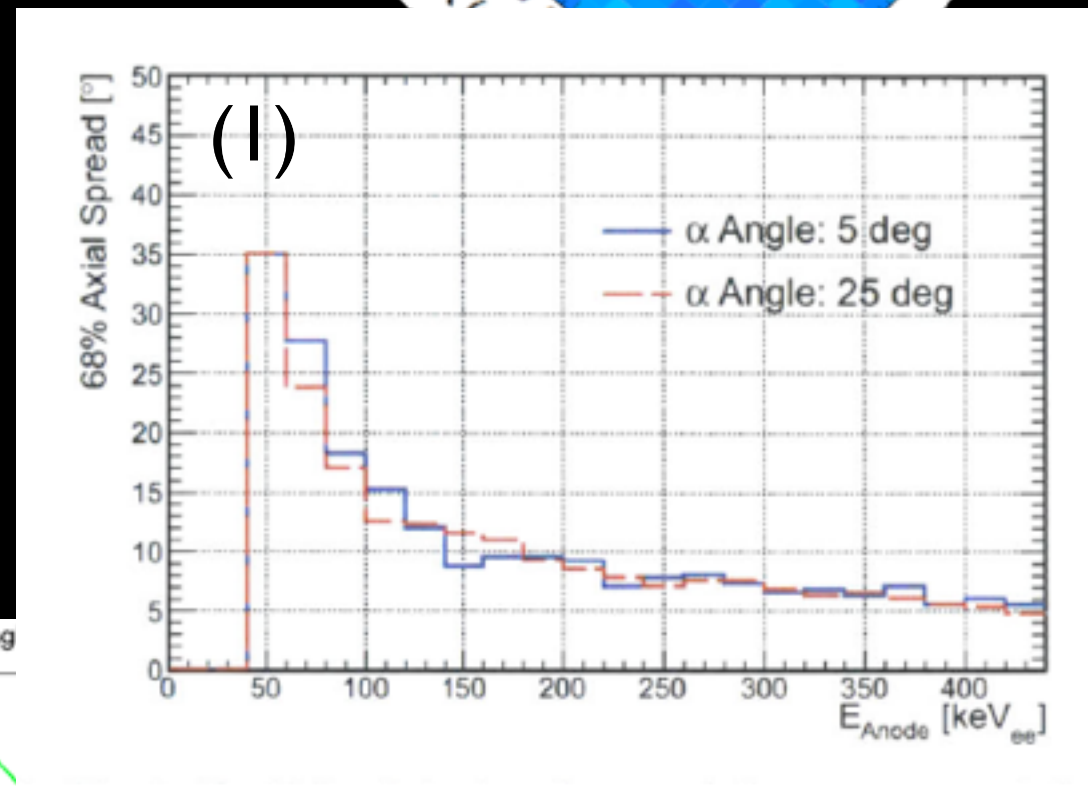
Track Reconstruction

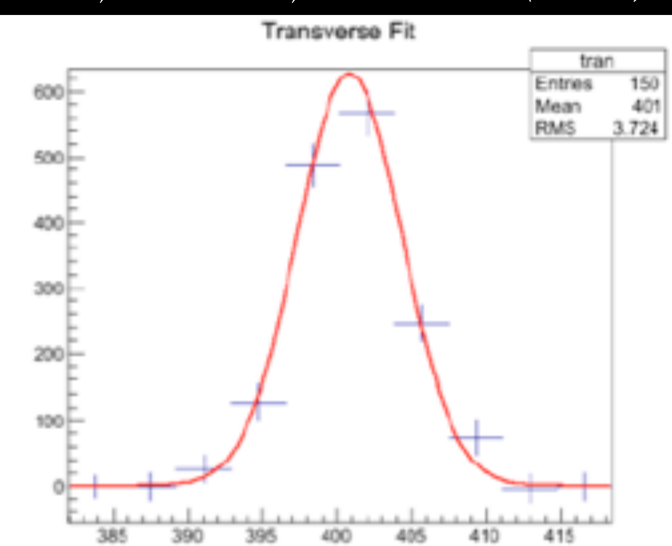


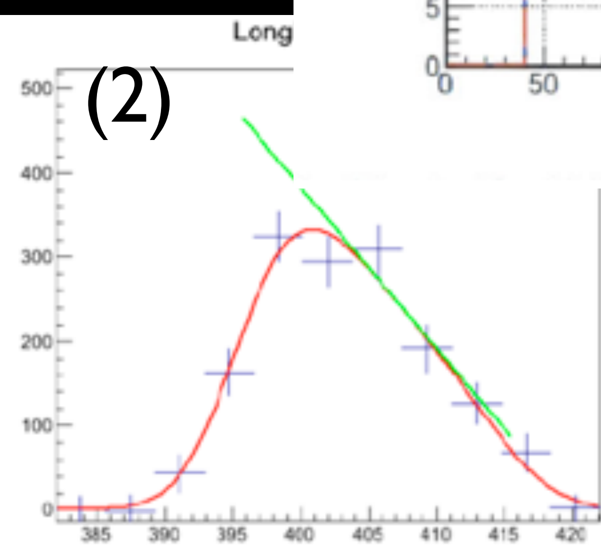
Measure energy from track intensity integral

Make use of the known profile of nuclear recoils from the Bragg curve to
(1) fit for the track parameters
 (range, angle)
(2) fit for the head-tail (H-T)
(3) assign confidence in H-T
 determination with likelihood
 ratio of two possible senses,
 cut on confidence

C, Deaconu, PhD thesis (2015)







J. Lopez, PhD thesis (2014)

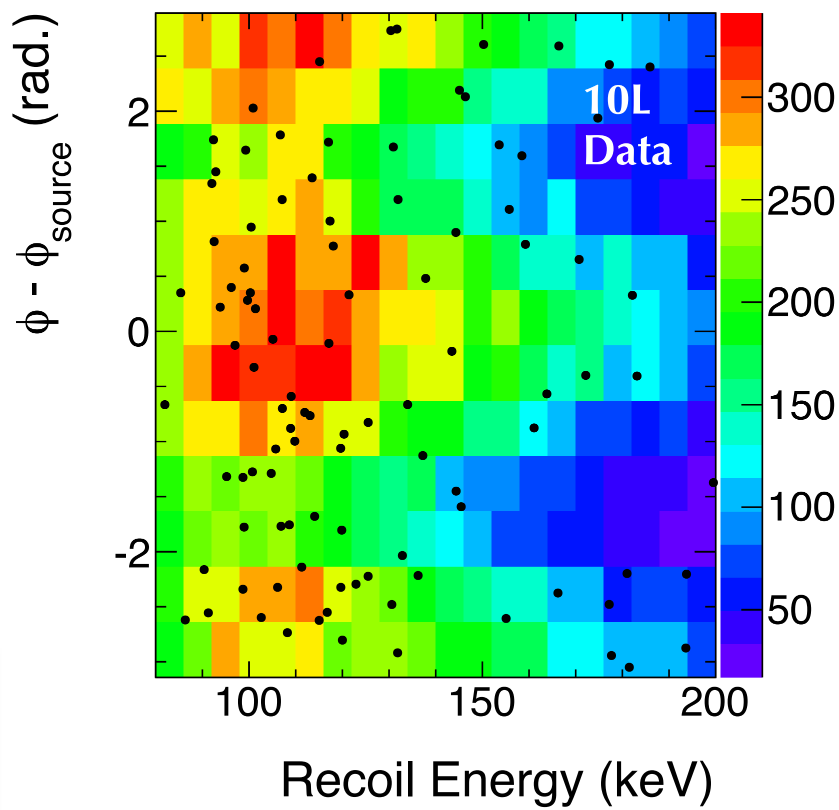
Directionality II

diffusion has a big impact!
- measure with 20, 25 cm drift

- find direction reconstruction depends most on track length, range/width>3 for head-tail ID,

C. Deaconu, PhD (2015), Phys. Procedia 261 (2015) 39

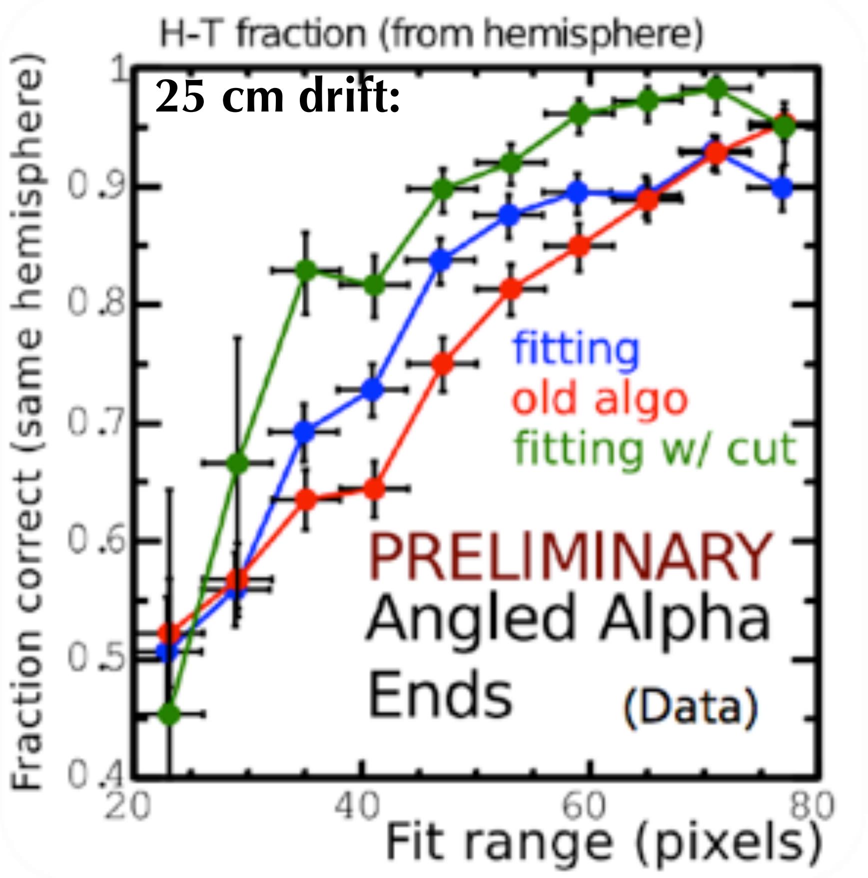
20 cm drift:



1D "sky map" for ^{252}Cf, and "WIMP " data (80-200 keV)

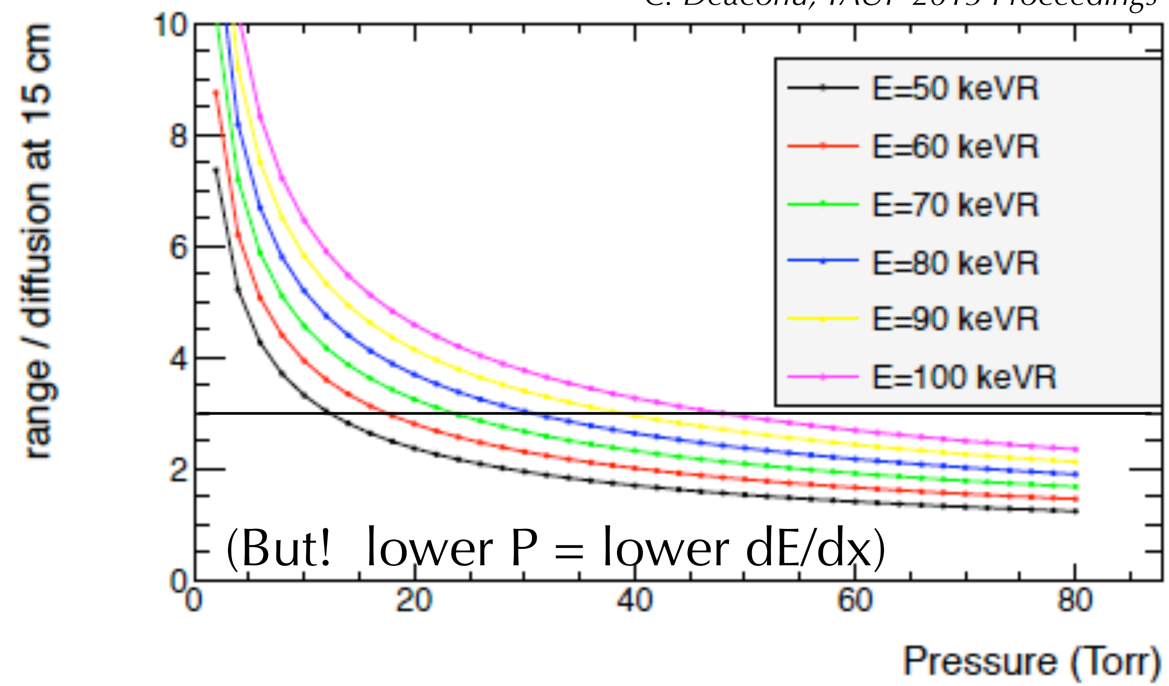
MC: 40° resolution at 80 keVr

A. Kaboth PhD thesis (2012)



Energy range equivalent ~50-200 keV

C. Deaconu, TAUP 2013 Proceedings

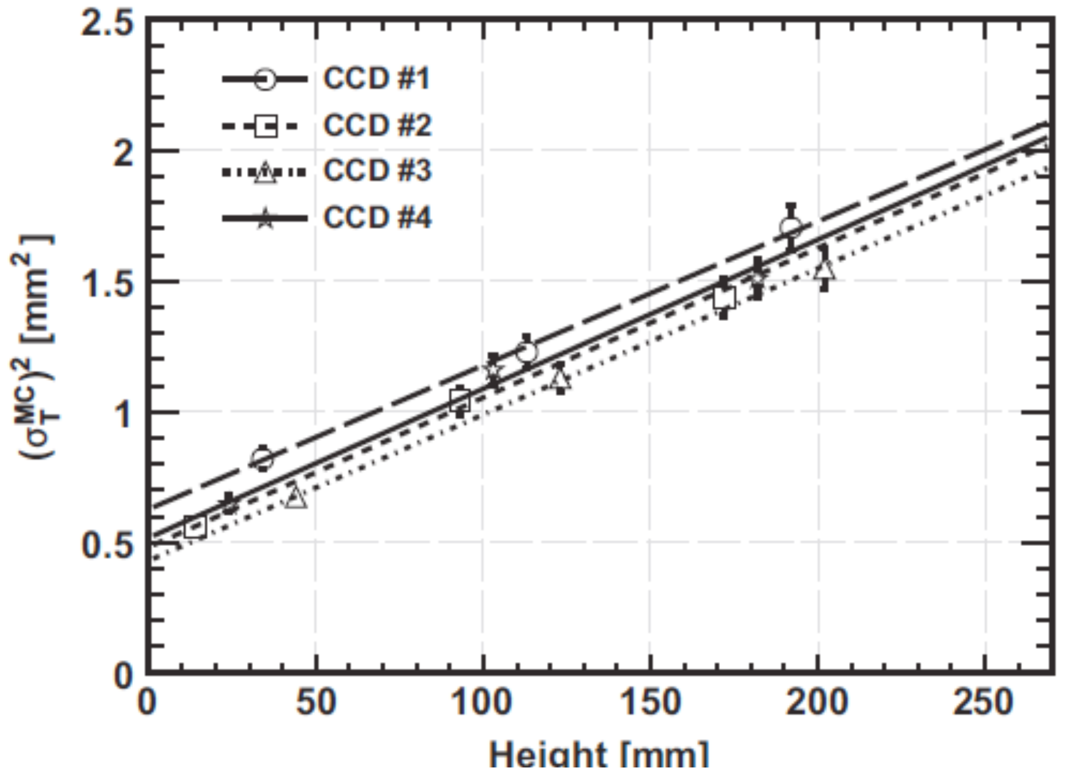


(But! lower P = lower dE/dx)

Diffusion Measurement

Measure track width from alpha source at known heights in detector,

- fit for two terms: $\sigma_T^2(z_{DRIFT}) = \sigma_{T,0}^2 + 2\left(\frac{D_T}{\mu}\right)\left(\frac{z_{DRIFT}}{E}\right)$



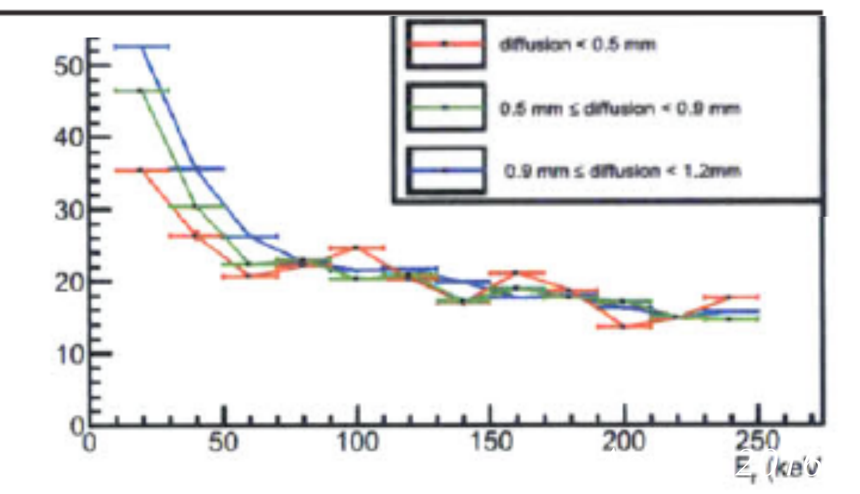
- find z-dependent term consistent with literature recommended value

L. G. Christophorou, et al, Journal of Physical and Chemical Reference Data 25 (1996) 1341

CCD #	D_T/μ (V)	$\sigma_{T,0}^{MC}$ (mm)
1	0.052 ± 0.005	0.79 ± 0.05
2	0.054 ± 0.005	0.69 ± 0.04
3	0.052 ± 0.005	0.66 ± 0.07
4	0.053 ± 0.005	0.72 ± 0.05

- constant term (straggling?) dominates until z~20cm, and z=25 cm for σ^2_T<1mm

J. Battat, JM, et al., NIMA 755 (2014)

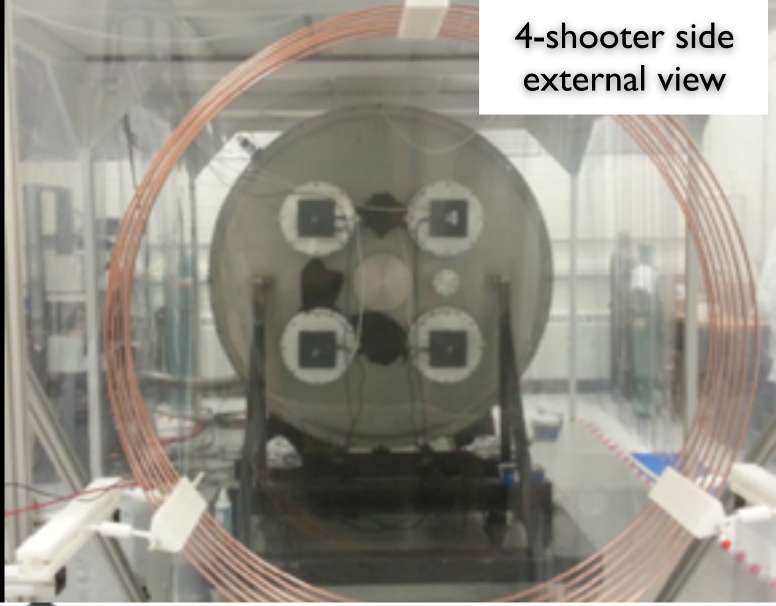


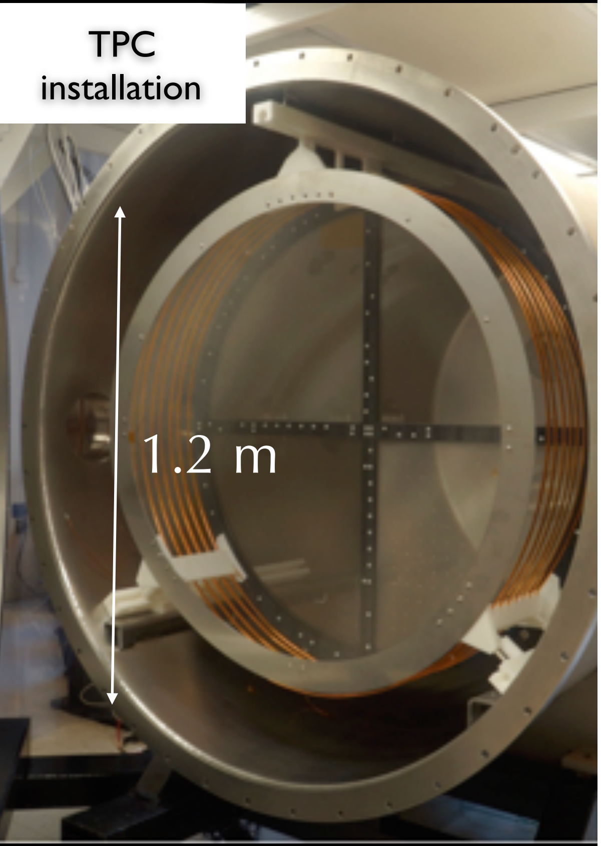
- sets a maximum drift length per TPC to be ~25 cm to preserve track direction

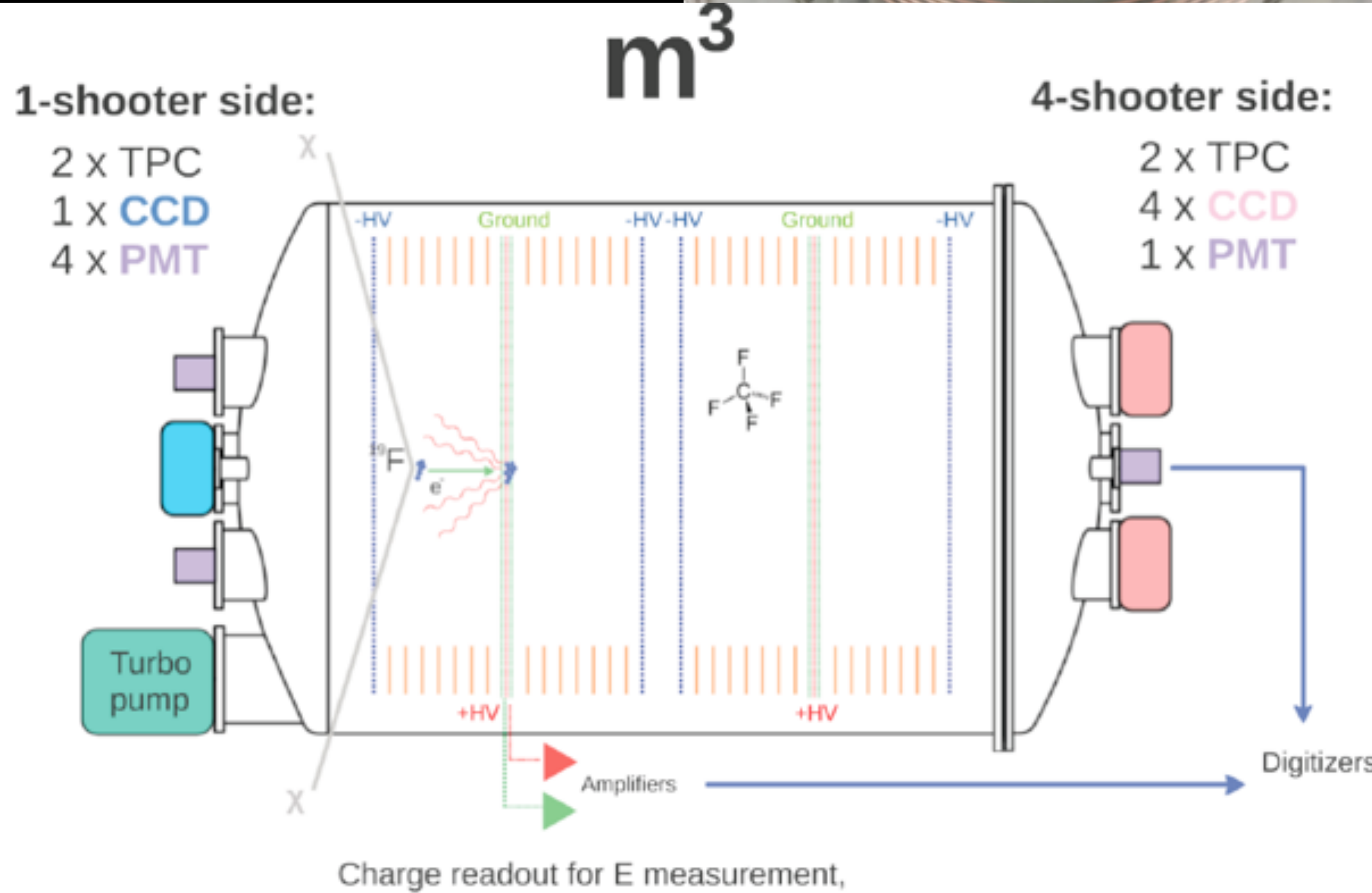
DMTPCino: 1 m³ Active Volume Module

prototype for large detector:
build many 1m³ modules, because of diffusion limit.

goal: achieve similar or better S:N per pixel,
for 35° resolution at 50 keVr in 1m³ module, and
R&D: 1 camera+lens/side (~0.005$/channel now)







Signal:Noise

Lower pressure (P) gives longer range (good!), higher gain (good!), but lower dE/dx (bad!!)

Signal size:

$$S = \frac{(\frac{E \times q}{w}) \times G \times (\gamma/e^-) \times \rho \times QE \times \eta}{N_{pixels/track}} \qquad (11)$$

Where:

- E = 50 keV the target nuclear recoil energy threshold at which DMTPC wants to be able to reconstruct the direction of tracks well
- q = 0.6 is the gas quenching and is defined as the fraction of energy released by a recoil in a medium through ionization compared with its total kinetic energy [14]
- w = 34 eV represents the mean energy required to produce an ion/e^- pair in CF_4, work function of the gas [7]
- G = 10^5 is the gas gain
- γ/e^- = 0.3, is the number of photo-electron pairs created as a result of the scintillation light produced
- ρ is the geometric acceptance of the lens $= \frac{1}{16(1+m)^2(f/\#)^2}$
- $\eta = 0.64$ is the combined anode (0.8), cathode (0.9) and detector window (0.9) transparency

Noise size:

$$N_{total} = \sqrt{N^2_{Shot} + N^2_{readout} + N^2_{Dark}}$$

To increase S:N: 1) increase geometric acceptance , 2) reduce *N*, 3) increase gas gain *G*

Optical System for Large Area Optical Readout

<u>comparison of 20L prototype vs. DMTPCino optical systems S:N</u>

20L *prototype*: 4x Alta CCD + Canon f/1.2lens

DMTPCino: 4-CCD side: Proline9000 CCD (0.01 e/pix/s dark rate) + Nikon f/0.95 lens

1-CCD side: Fairchild 486 CCD (0.0001 e/pix/s dark rate) with quad readout + large angle-of-view Canon f/0.95 lens

calculation inputs:

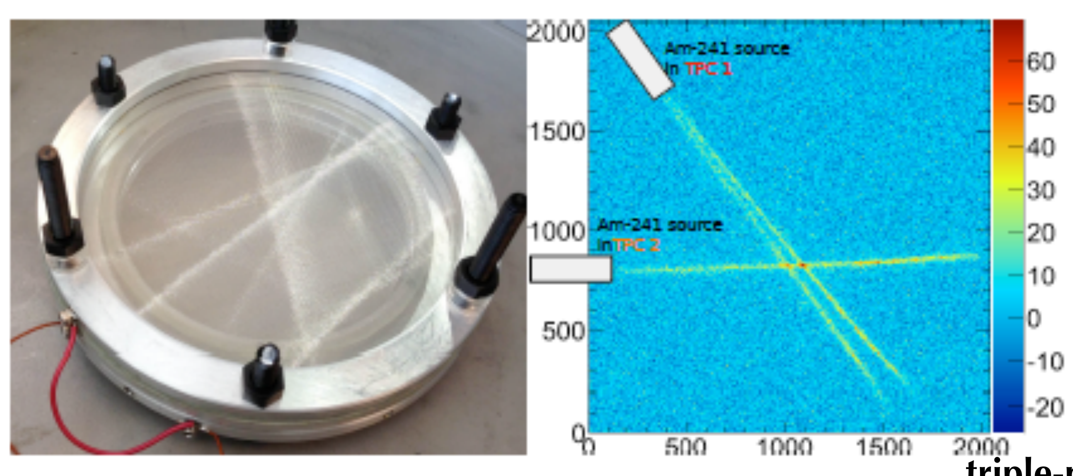
- 30 Torr pressure: 2.5 mm long track, 1 mm wide @ 50 keVr to estimate S/pixel
- gas gain = assume 100,000k for DMTPCino, vs. 65,000 gain for 20L prototype
- dark current rate and read noise from camera specs (confirmed in in-situ measurement)
- measured scintillation spectrum, Y/e-, lens transmittance vs. wavelength, lens vignetting

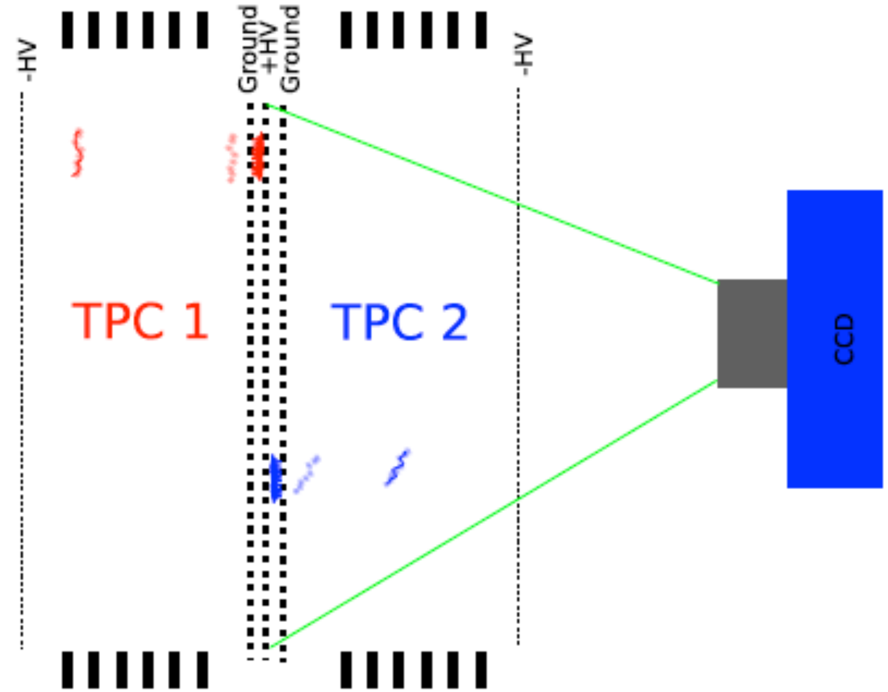
Lens/Camera	F(cm) / f#	pixel (um)	sensor diag. (cm)	FoV (cm)	m	acceptance (rho)	read noise (e-)	vixel size (um) (map to 1 pixel)	S/N (e-/e-)
DMTPCino 1-CCD side	5/0.95	15	6.14	$(113)^2$	18.4	2E-04	7	276	189/16 = 12
DMTPCino 4-CCD side	5/1.2	12	3.66	$(57)^2$	15.6	2E-04	10	243	95/14 = 6.8
20L prototype	8.5/1.2	24	2.45	$(16)^2$	6.65	5E-04	10	160	87/13 = 6.3

empirically: S:N>15 results in ~20 keVr track-finding threshold -> bin 2x2 before readout

Gas Gain R&D

triple mesh amplification: one camera images 2x 25 cm drift regions





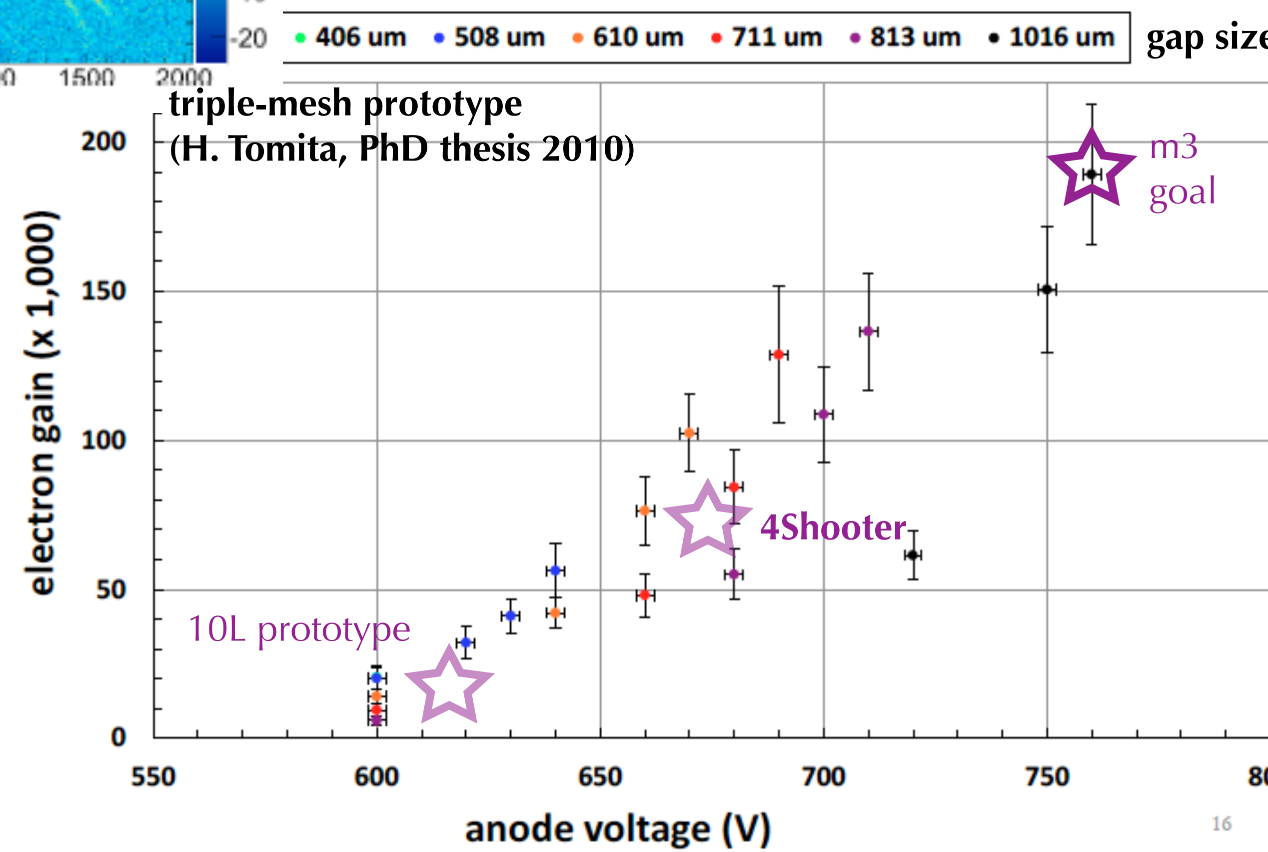
demonstrated high gain in small prototypes, 50-200k

optimizing gap size, pitch to maximize pixel signal:noise,

•10x gain with 2x gap size

price: 25% amplification region diffusion tails increase

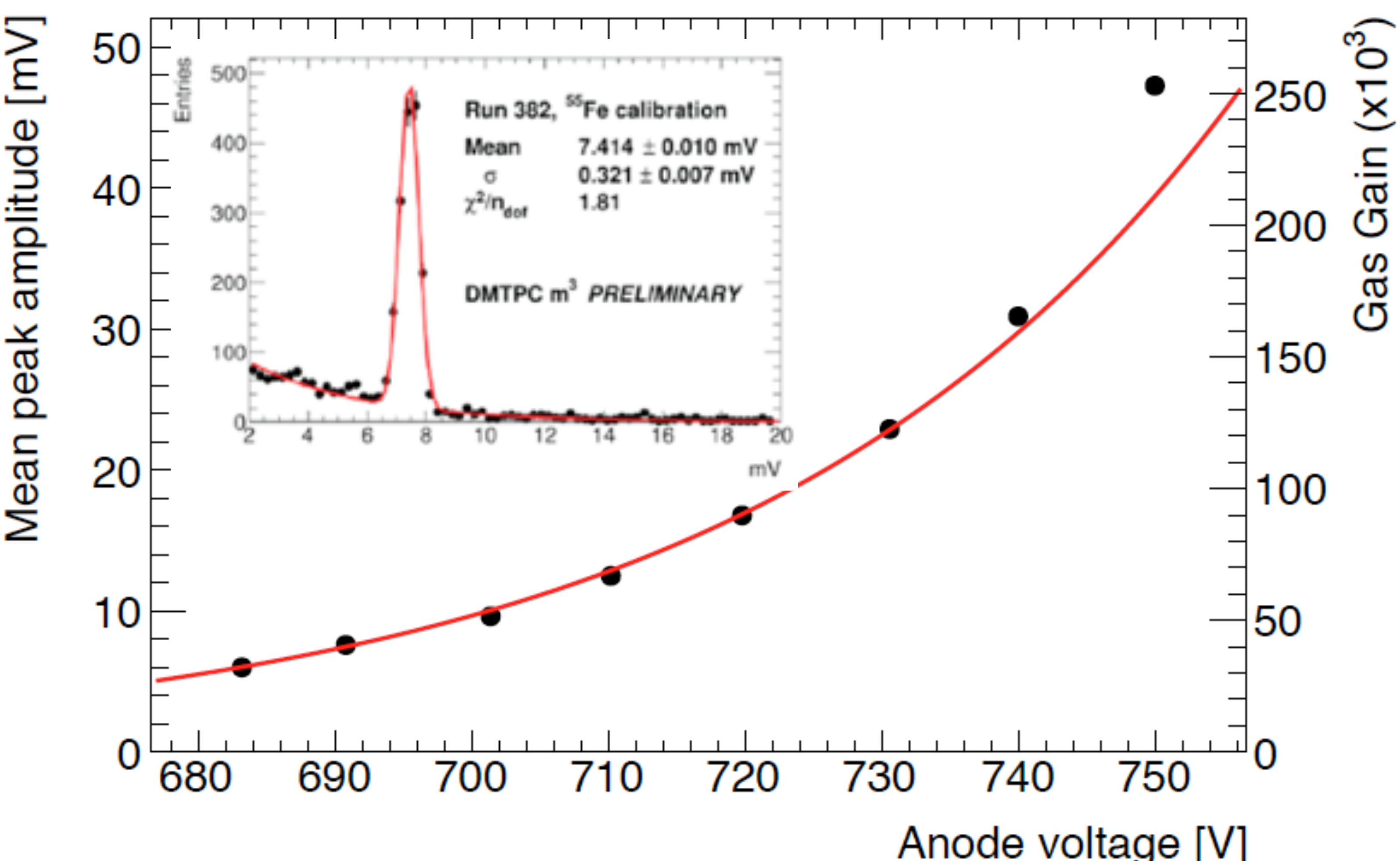
H. Tomita, PhD thesis (2010)

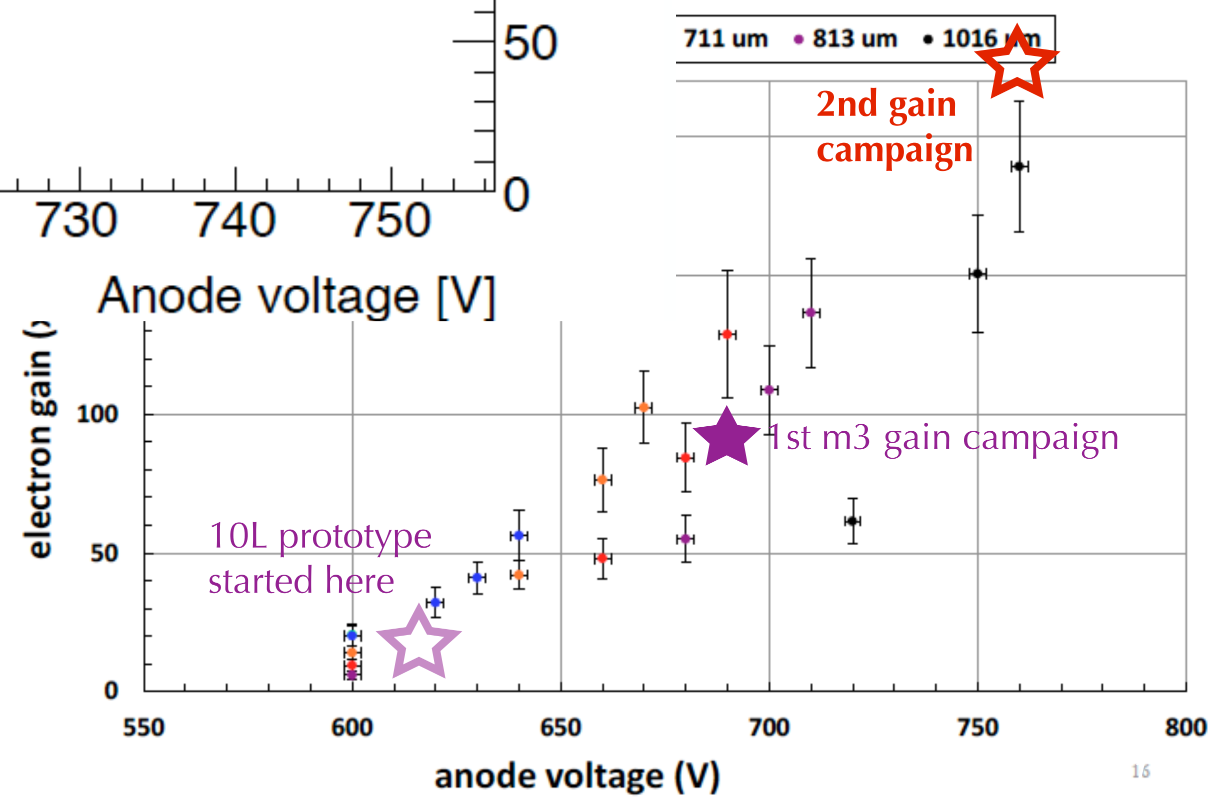


DMTPCino: Gas Gain Calibration

higher gain = lower energy threshold.

Fe-55 source (5.9 keV) deployed to measure absolute gas gain vs. anode voltage, at 30 Torr operating pressure.

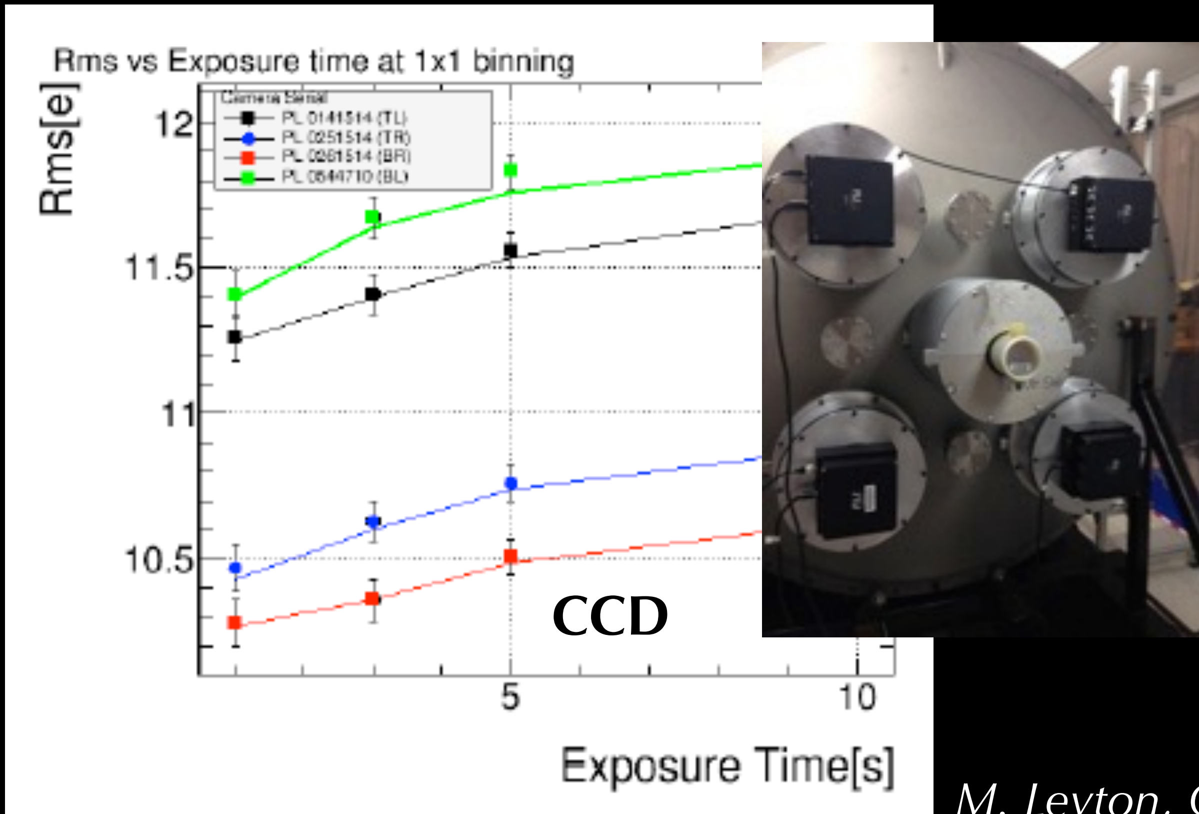


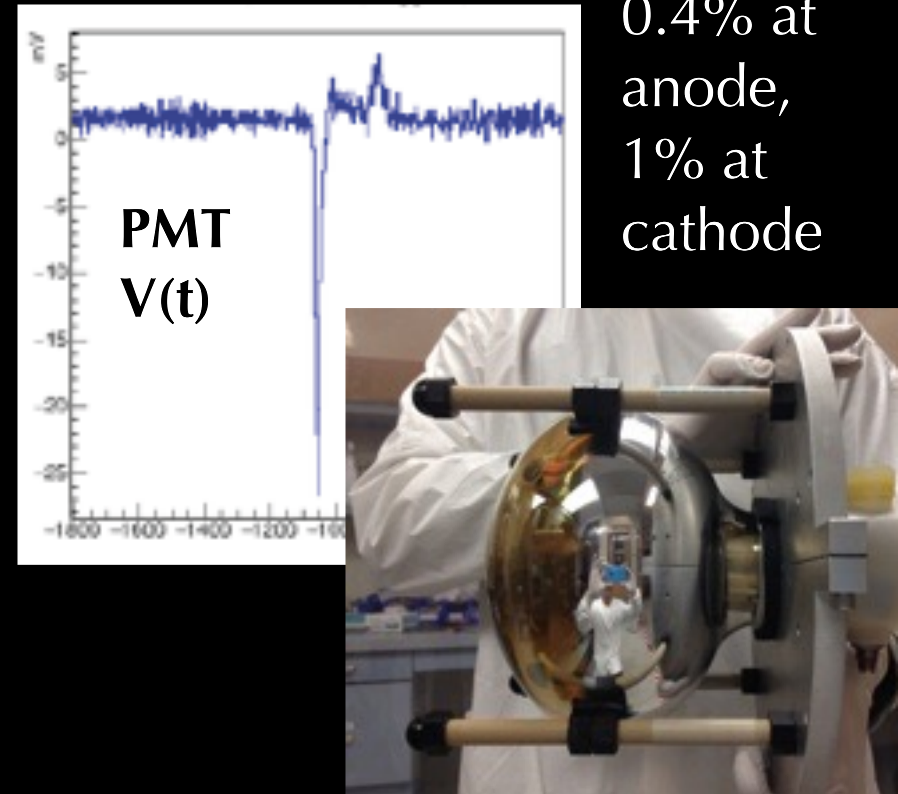


result: gain>250,000 can be achieved = factor of 4x higher than previous operating point of 65,000 (in 20L prototype), 25x 10L prototype operating point.

DMTPCino: Integration of Readout Channels

Optical: CCD + PMT

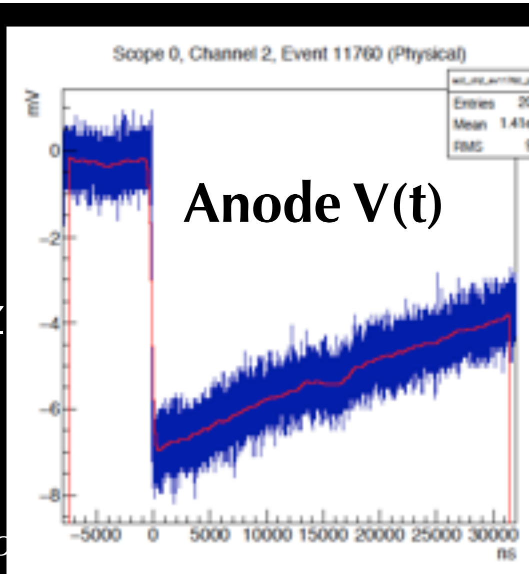


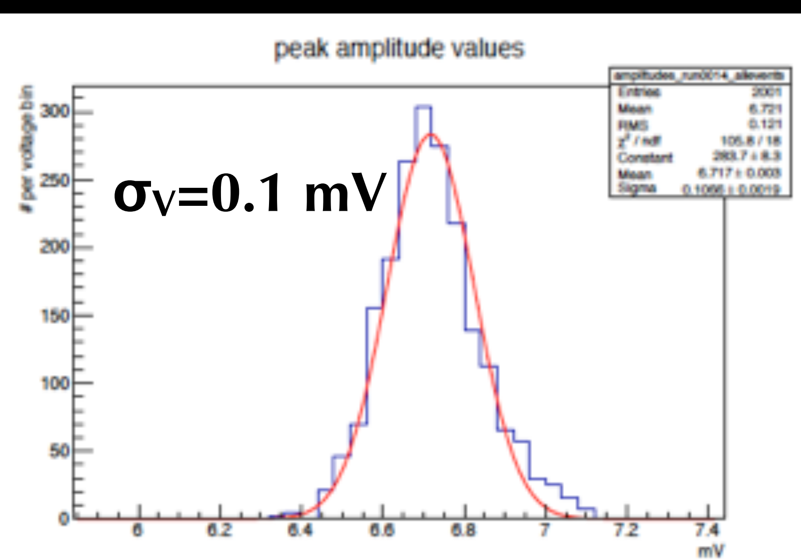


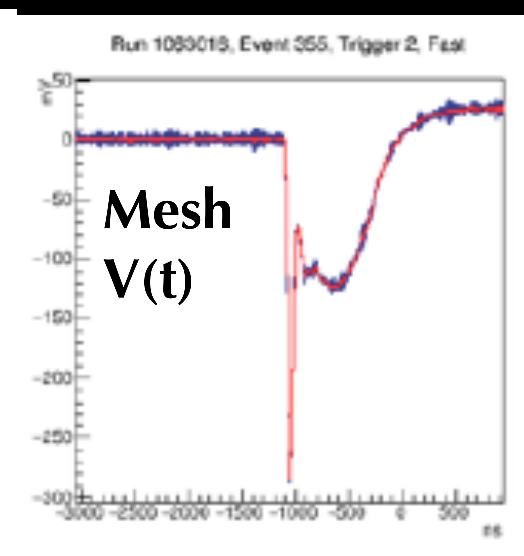
PMT dΩ
0.4% at anode,
1% at cathode

M. Leyton, G. Druitt, N. Guerrero

Charge:
Anode +
Mesh @
500 MHz
readout

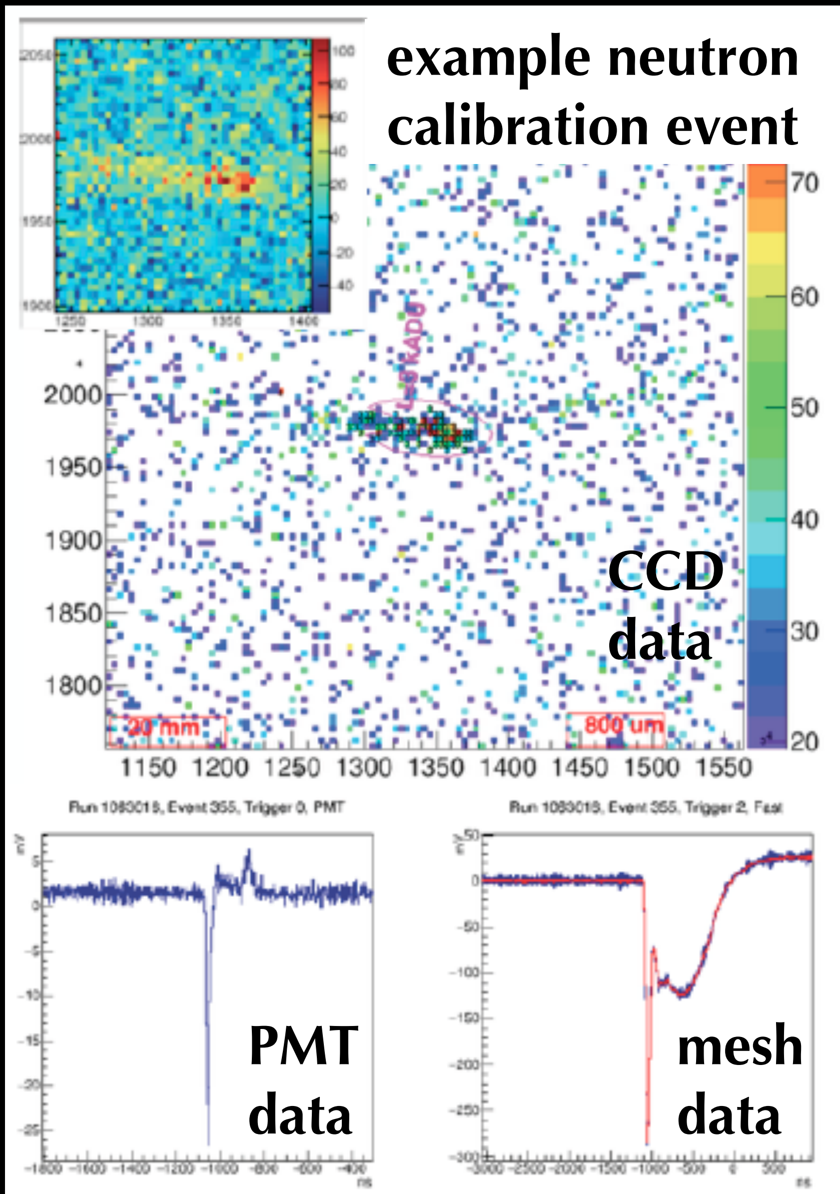


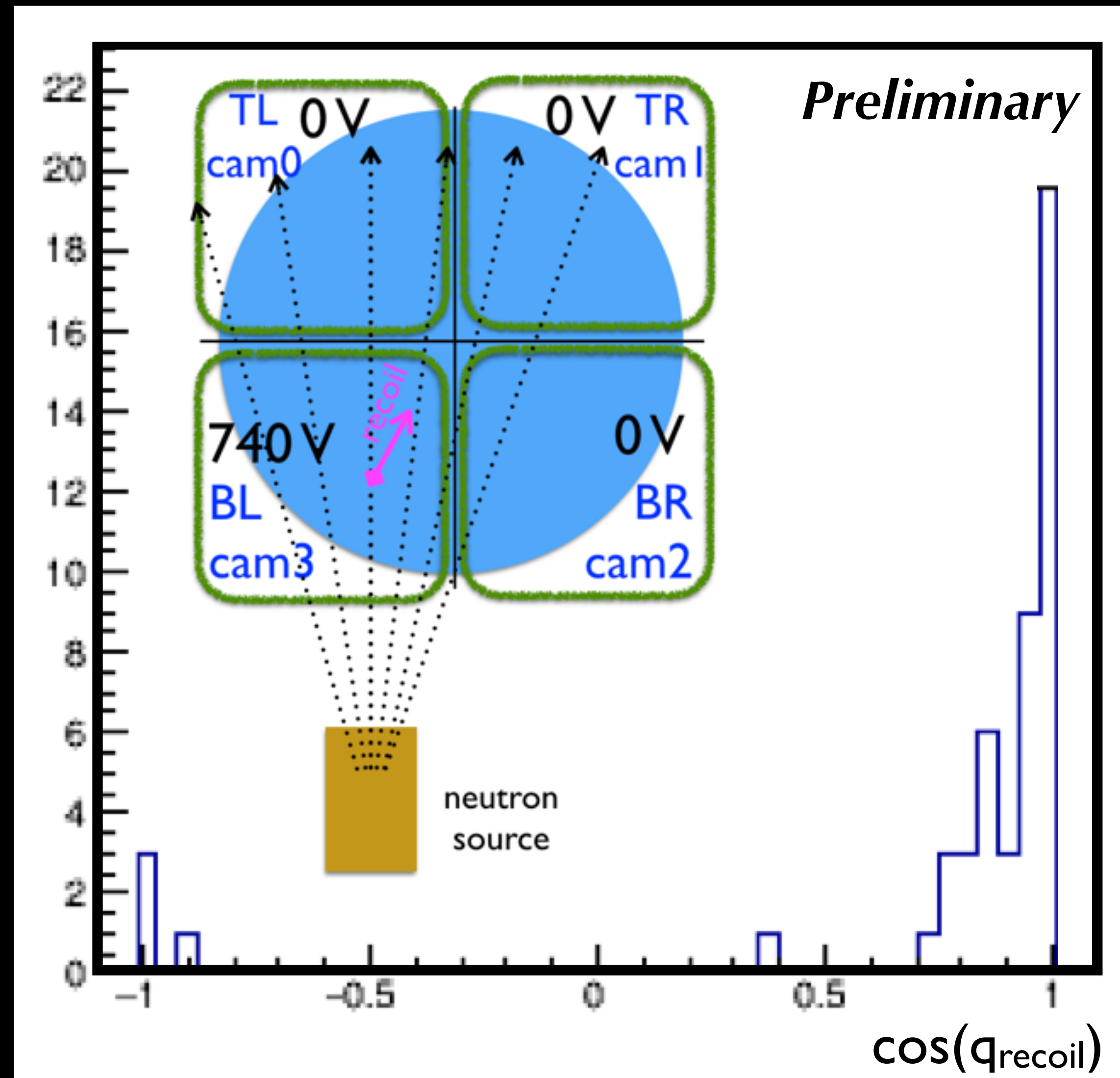




DMTPCino: Direction Calibration with AmBe Neutron Source

- Stable operation at 150k gain for 4 weeks. Coincident signals in all readout channels!
- Clear excess in n source direction in high energy events (q_{recoil} = recoil-source angle)



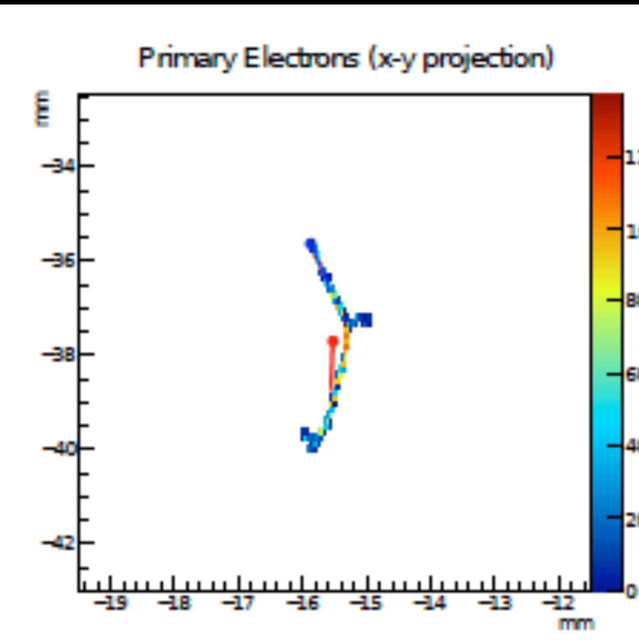


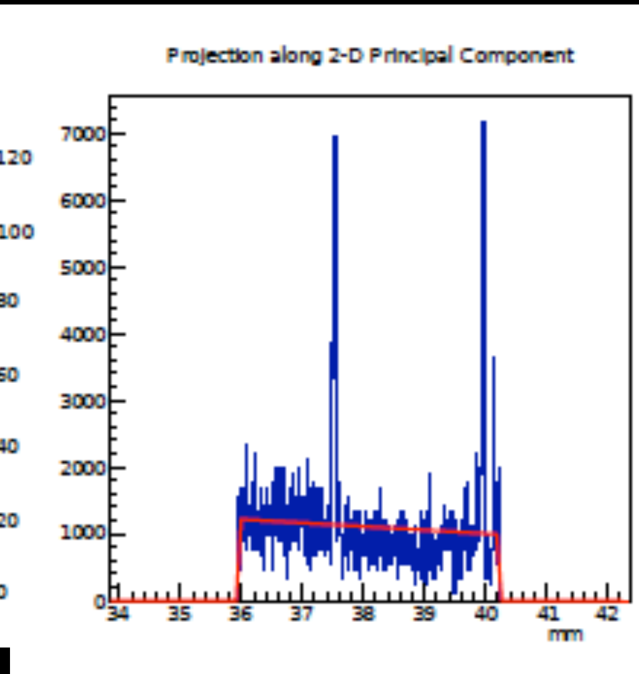
J. Battat, et al., Physics Reports 662 (2016) 1-46

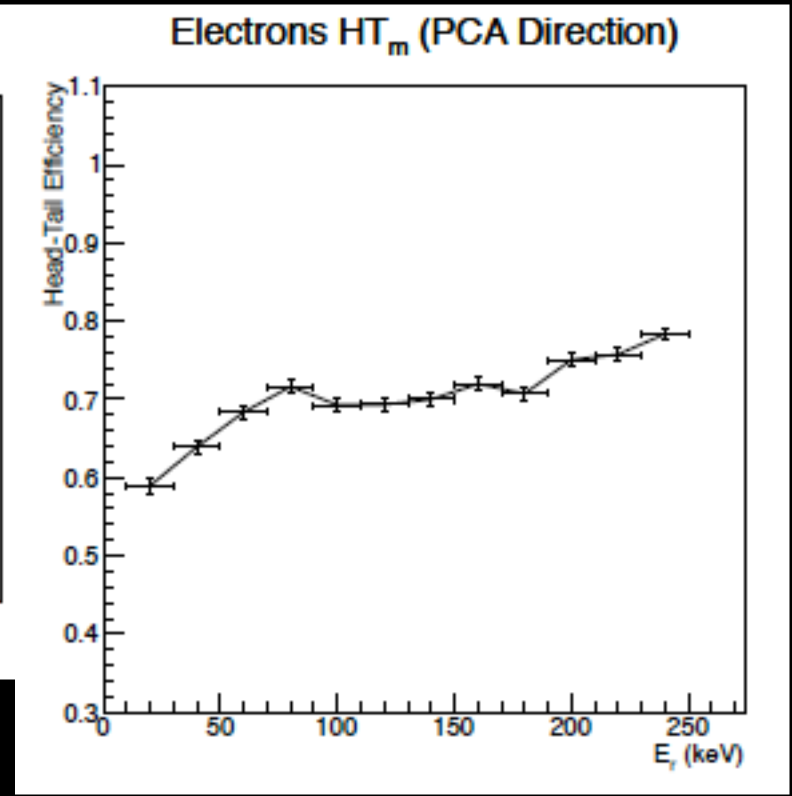
Full Microphysics Simulation

(C. Deaconu CYGNUS'15)

Generated Ionization:





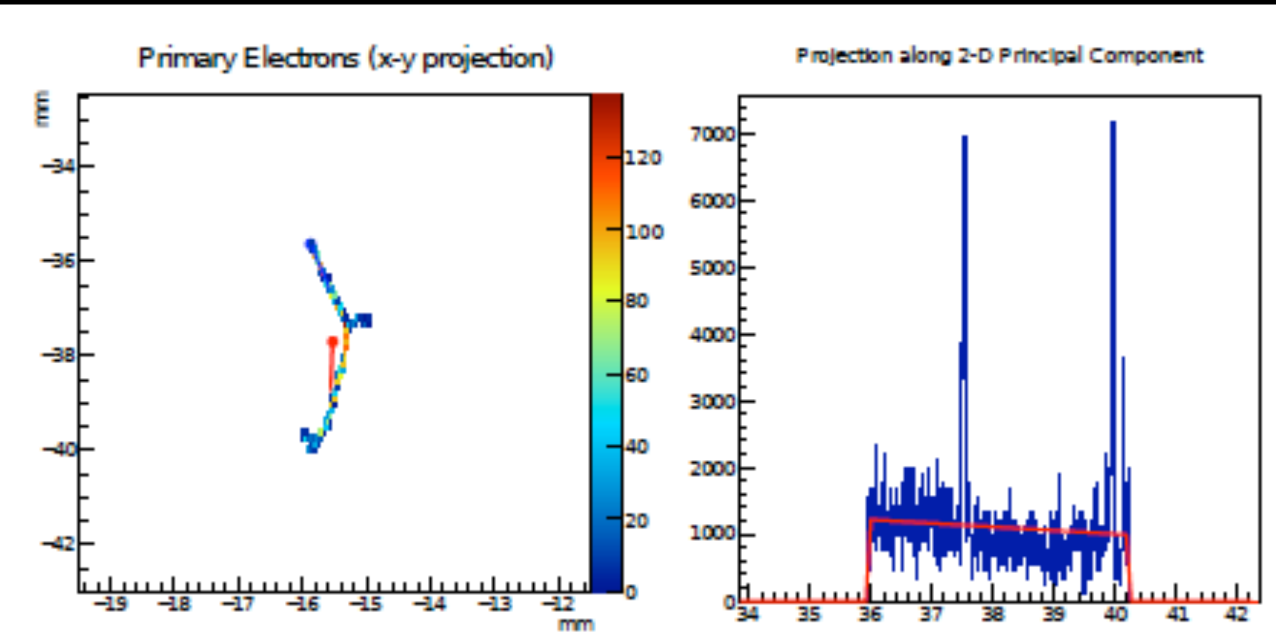


(TRIM simulation)

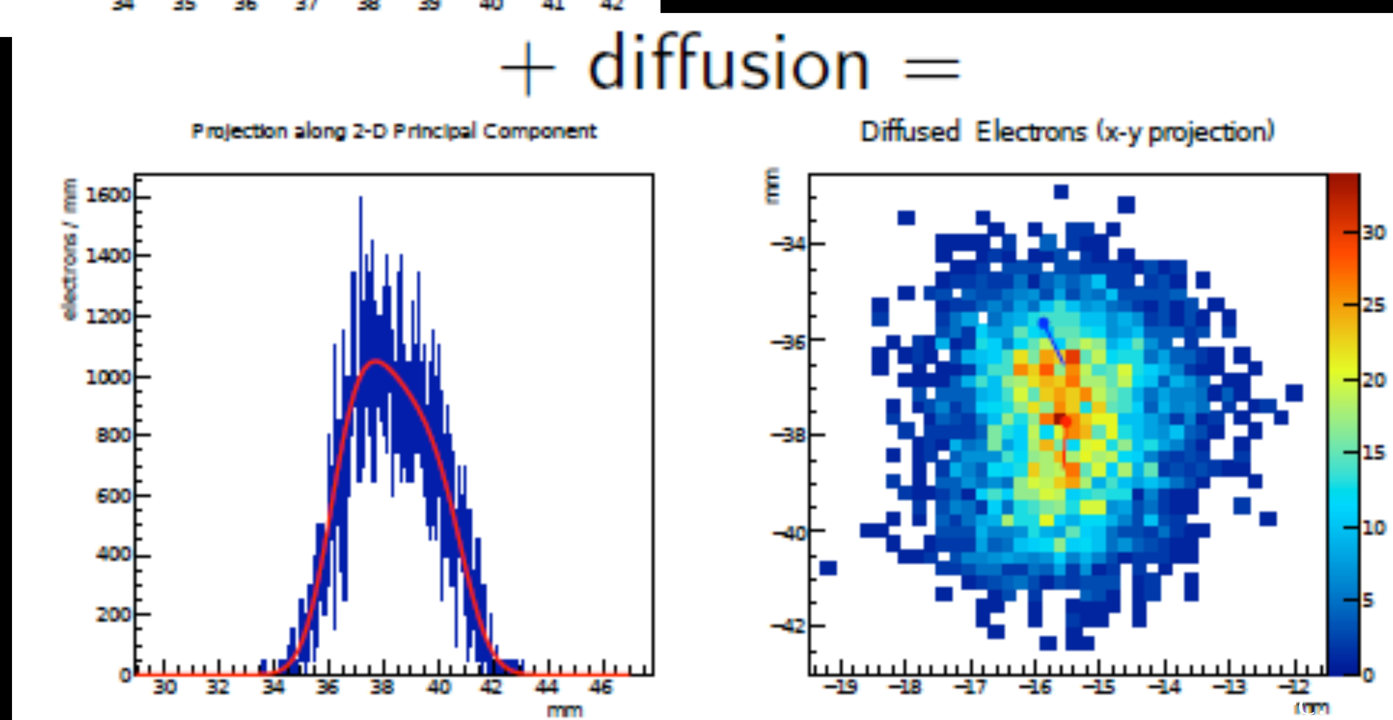
Full Microphysics Simulation

(C. Deaconu CYGNUS'15)

Generated Ionization:



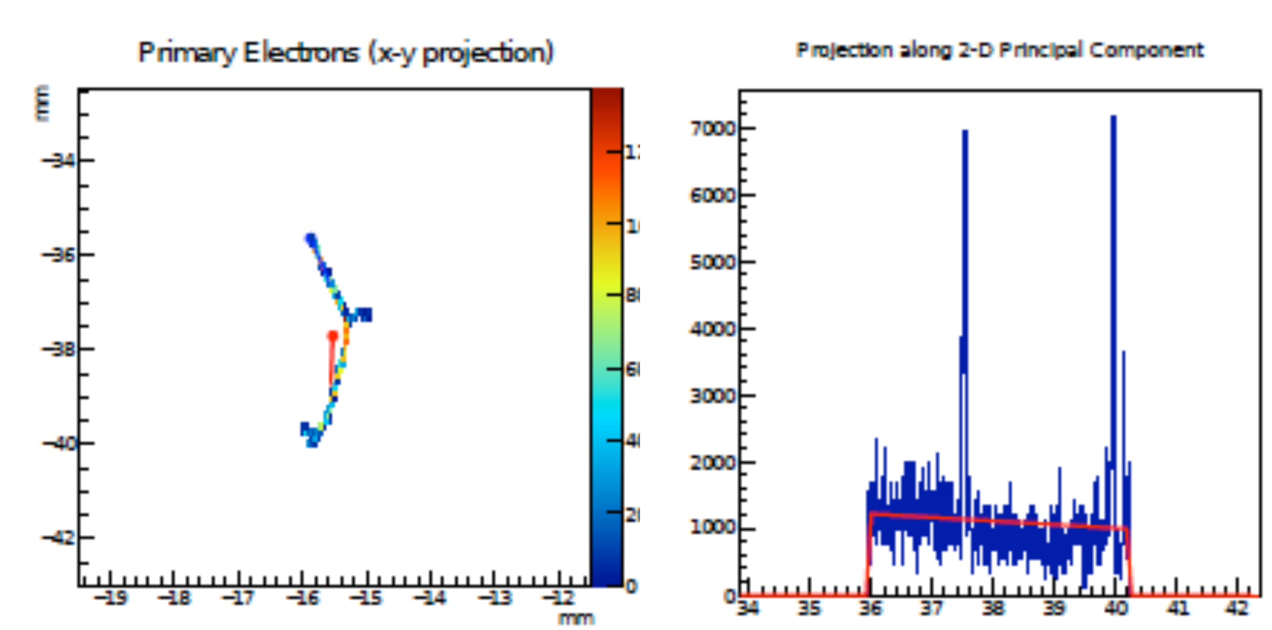
TRIM simulation
+ HEED cluster generation
+ MagBoltz



Full Microphysics Simulation

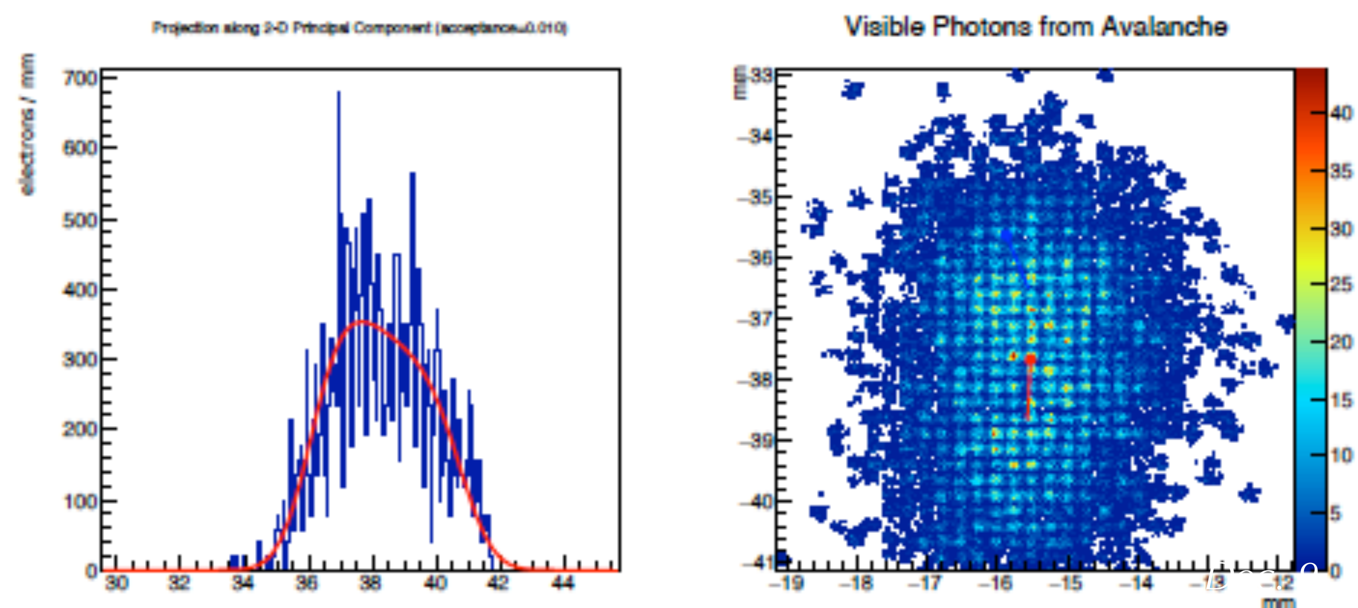
(C. Deaconu CYGNUS'15)

Generated Ionization:



TRIM simulation
+ HEED cluster generation
+ MagBoltz
+ GARFIELD

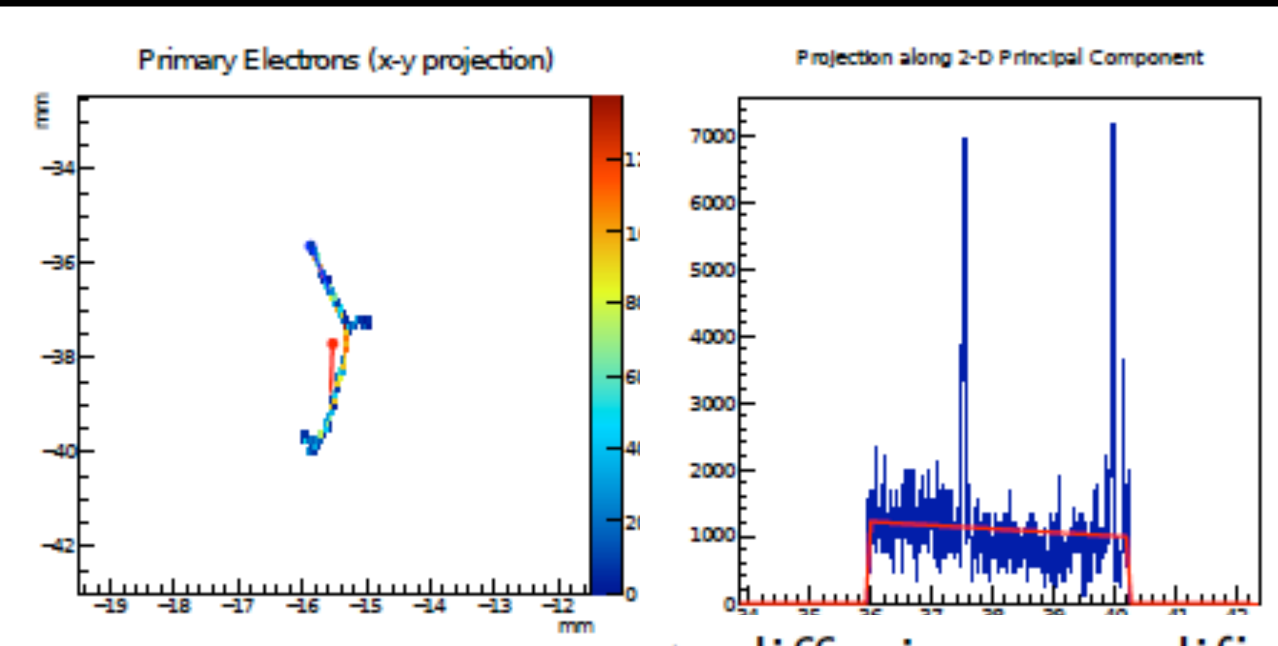
+ diffusion and amplification =



Full Microphysics Simulation

(C. Deaconu CYGNUS'15)

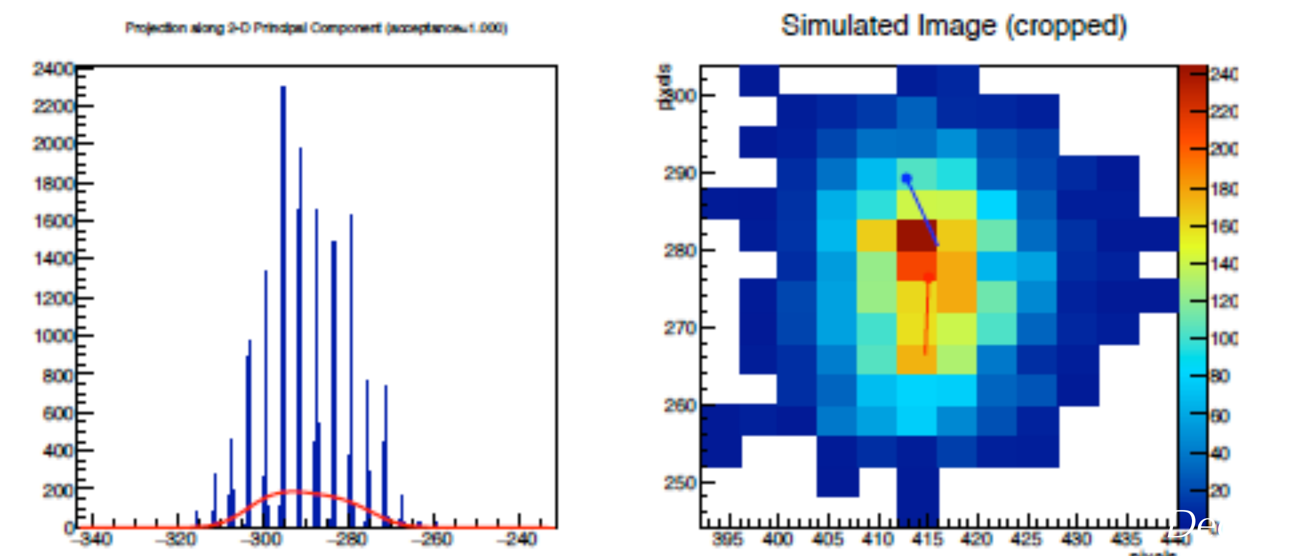
Generated Ionization:



TRIM simulation
+ HEED cluster generation
+ MagBoltz
+ GARFIELD
+ readout model

+ diffusion, amplification, attrition, binning

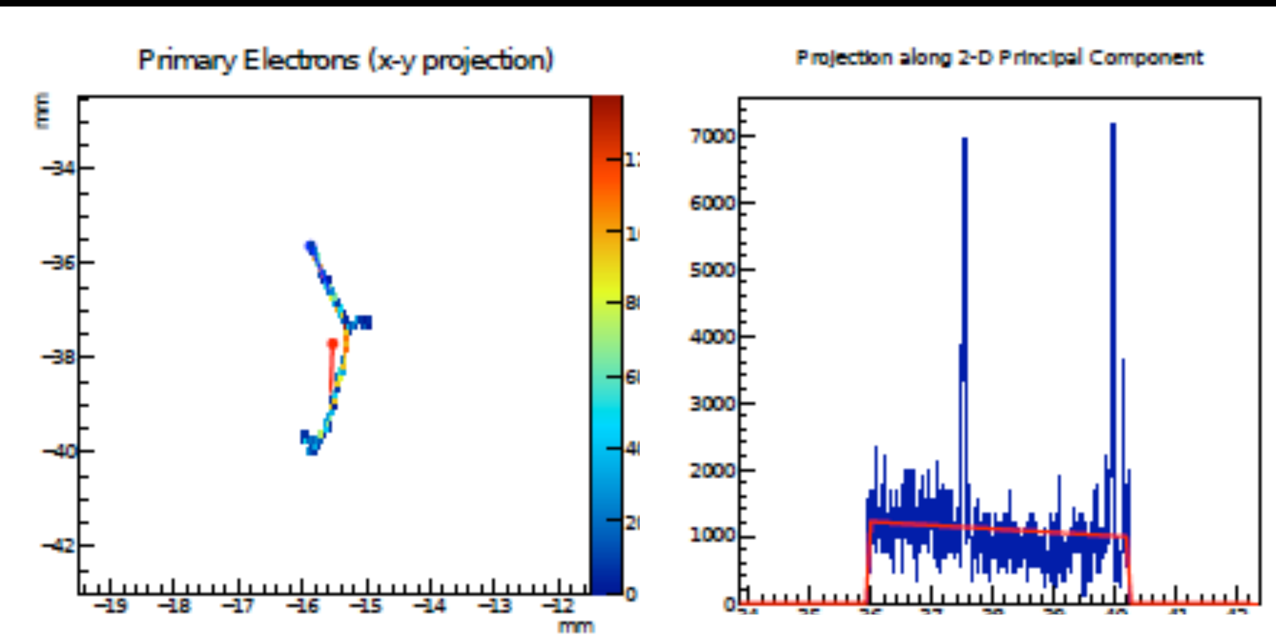
=



Full Microphysics Simulation

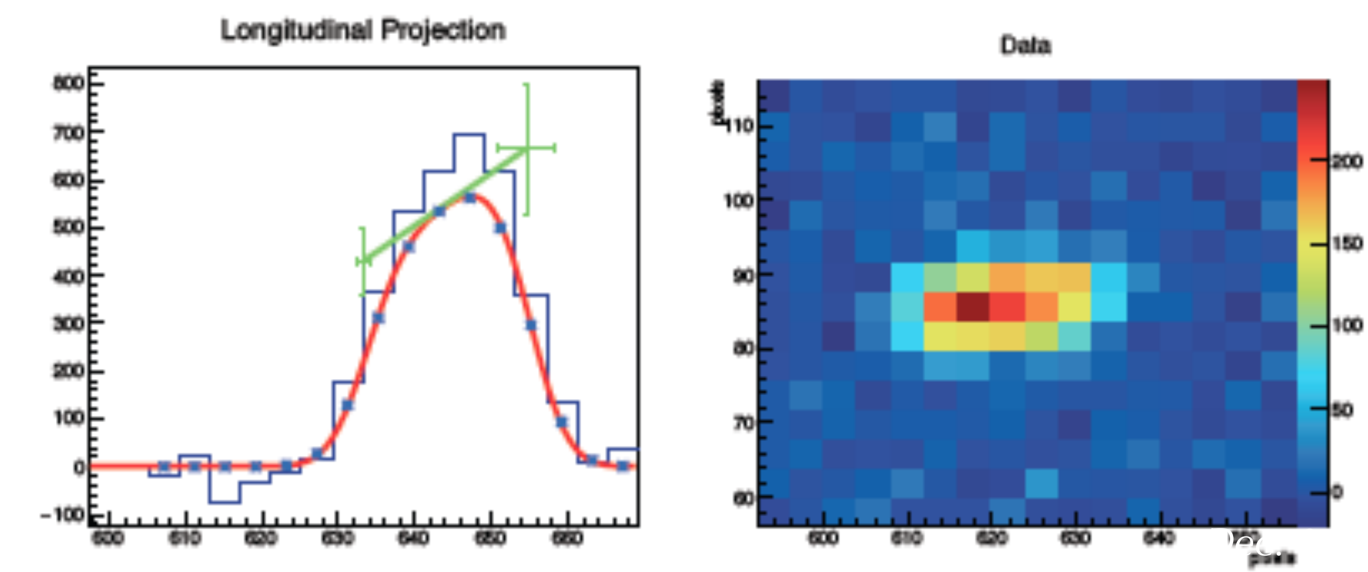
(C. Deaconu CYGNUS'15)

Generated Ionization:



TRIM simulation
+ HEED cluster generation
+ MagBoltz
+ GARFIELD
+ readout model
+ cluster finding
+ 2D likelihood

+ track reconstruction

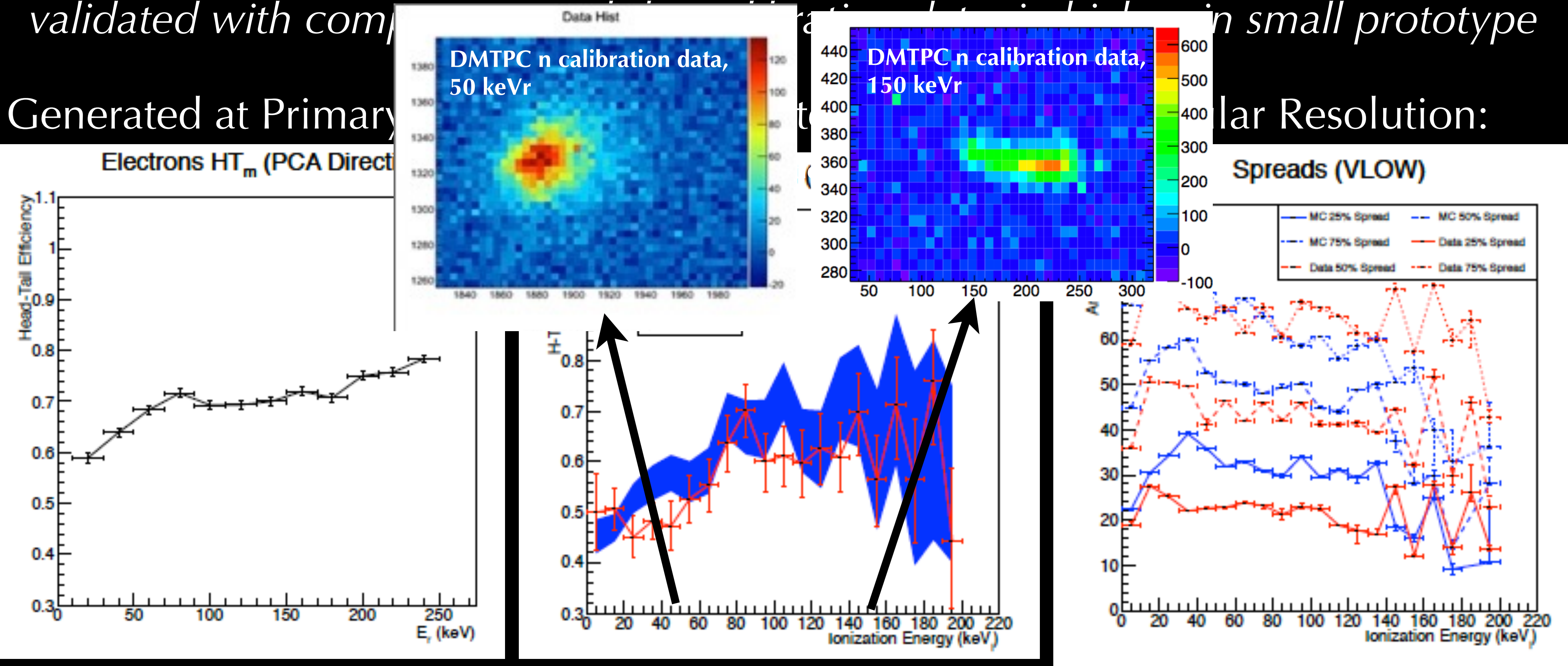


Full Microphysics Simulation

(C. Deaconu CYGNUS'15)

validated with comp … *n small prototype*

Generated at Primary … lar Resolution:

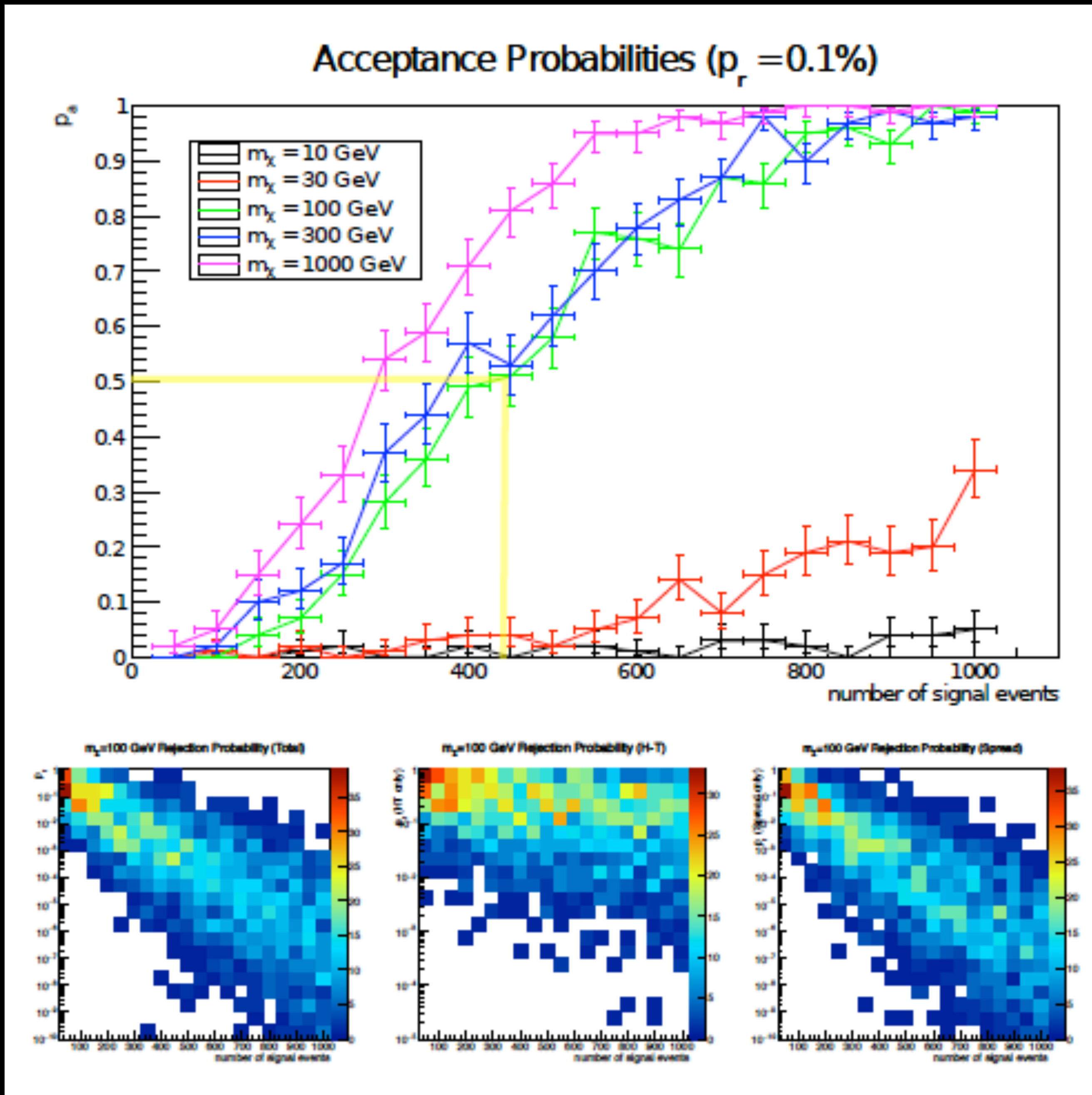


C. Deaconu, PhD thesis (2015)

Bottom lines:

- we are reconstructing direction (including head-tail) at ~physics limit from straggling of primary F ion. Need to reduce ion straggling! Lower Z gas, i.e. He?
- axial resolution is ~40 degrees (FWHM) at 50 keVr
- TRIM predicts ~50% larger angular spread than observed (measure straggling!)

DMTPCino Sensitivity Projection



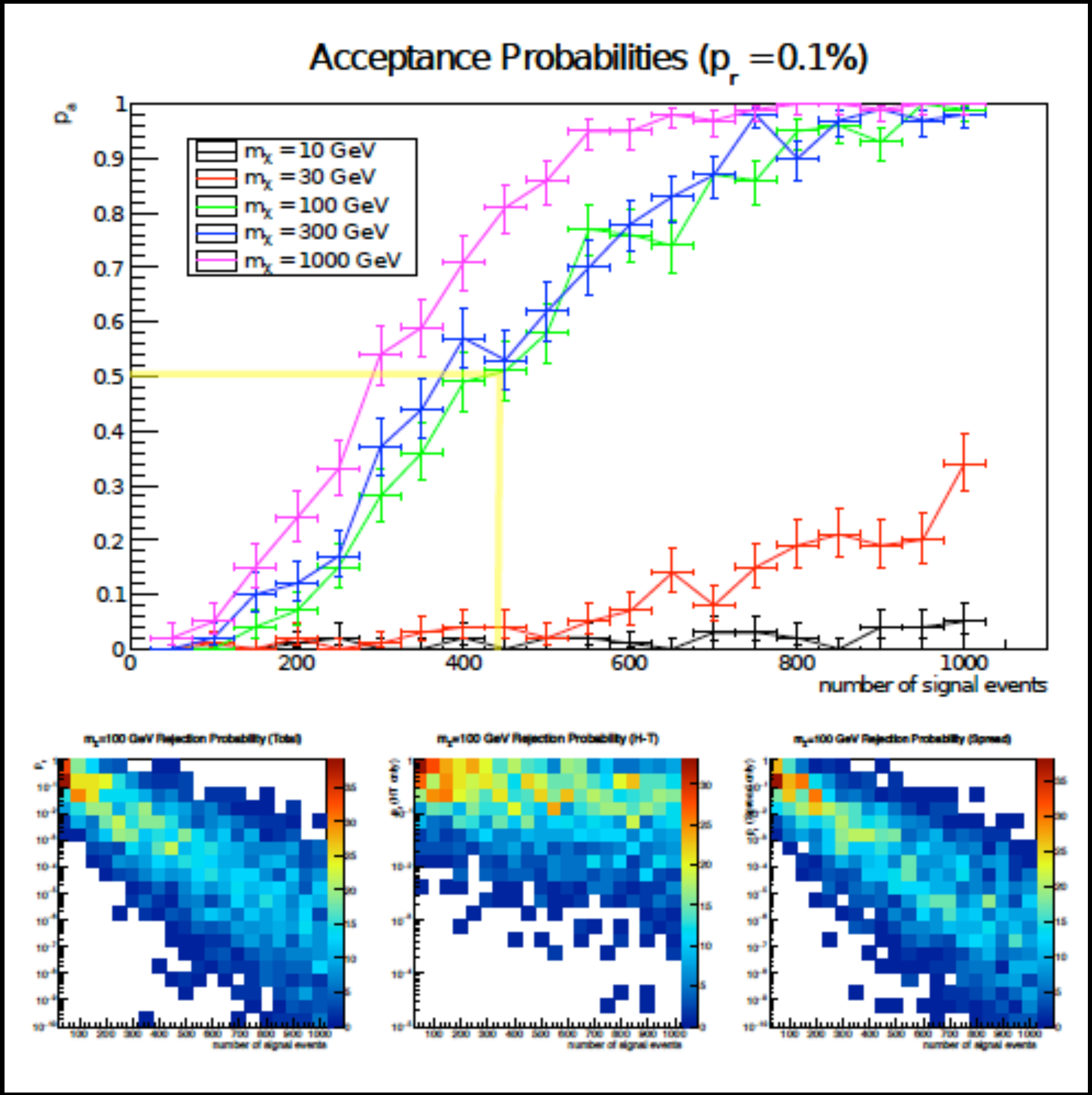
C. Deaconu et al., sub. Phys.Rev.D (2016)

Number of events required to observe the dark matter wind?

Analysis assumptions

- Use physics model tuned on data, assume 100k gain
- simulate *n* experiments, compute forward fraction and axial spread per bin
- calculate *p* of obtaining these values from isotropic distribution, and combine bins using Fisher's method
- Result: need 450 events to measure anisotropy at 3σ in >50% of experiments.

DMTPCino Sensitivity Projection



C. Deaconu et al., sub. Phys.Rev.D (2016)

- Result: need 450 events to measure anisotropy at 3σ in >50% of experiments.

= 500 [300] m3-years for 100 (1000) GeV/c^2 DM at 1 fb SD xsec on F (=25 kg-years exposure)

e.g. DEAP veto: 200 m^3

Outline

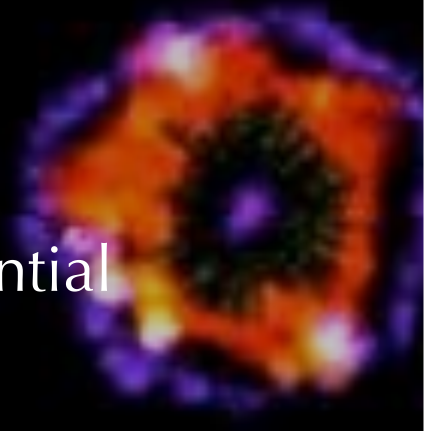
Physics Motivation

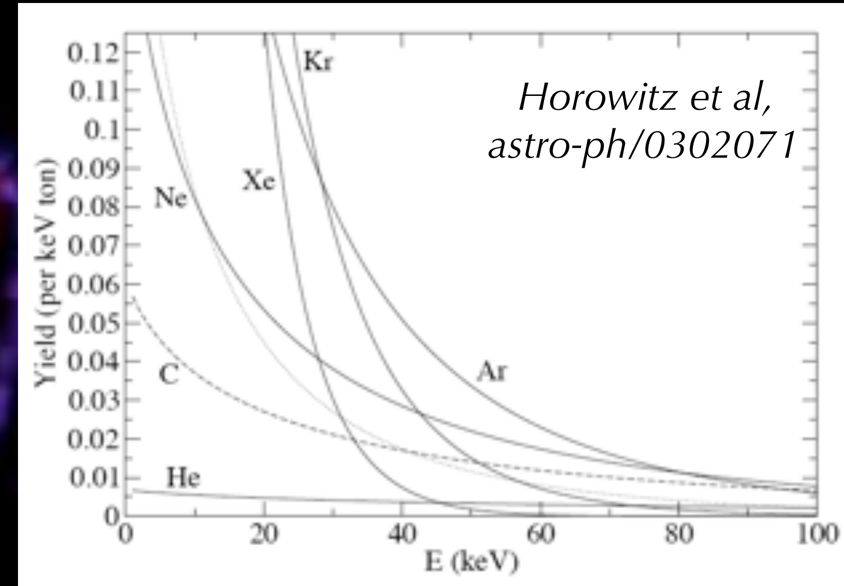
Detector Development
-Experimental Considerations for Dark Matter Searches
-Direction Measurement Progress in DMTPC

Outlook for Large Exposure
-Geo-Neutrino Sensitivity
-HPTPC for Neutrino Physics

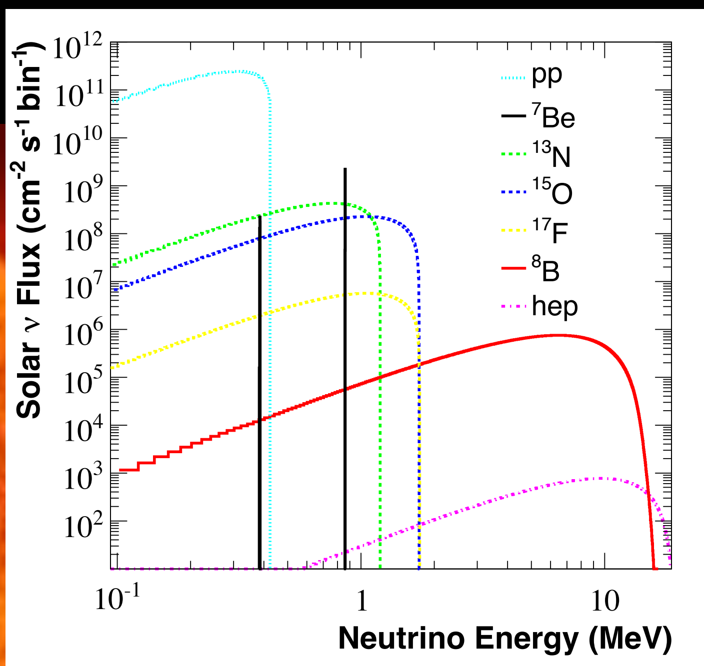
Low Background Frontier

tonne scale, keV threshold,
low background detectors
with directionality have potential
for first observations of...



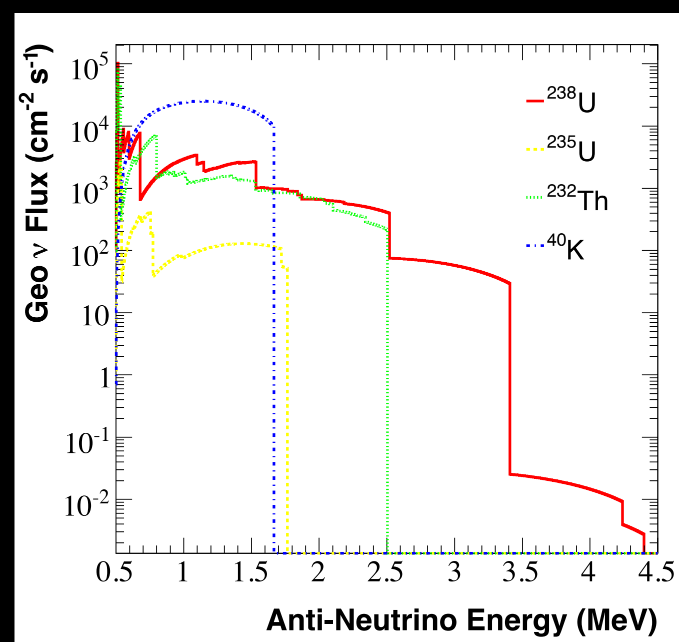


Supernova
neutrinos in NC, flux and spectrum



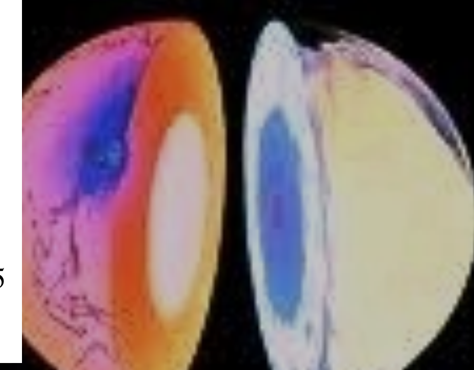
neutrino-nucleus coherent
elastic scattering of solar
neutrinos *JM, P. Fisher, PRD76:033007*

with direction measurement:



Leyton, Dye, JM, sub. Nature (2016)

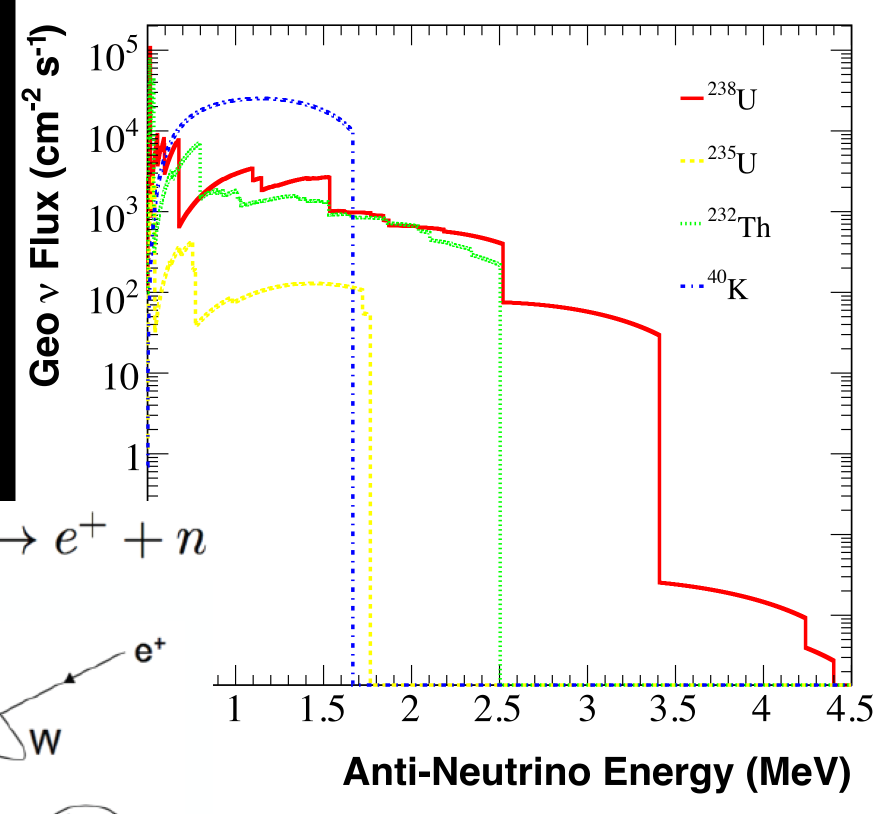
^{40}K geo-
neutrinos



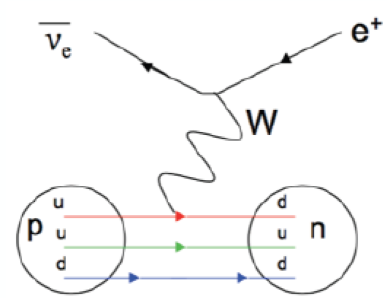
Geo-Neutrinos

U, Th geo-nus first observed by KamLAND, then Borexino using inverse beta decay

- rate ~4 events/100 ton-year
- 2.5x rate from BSE-based model (KamLAND), 1.6x (Borexino) *Mantovani et al., PRD69:013001 (2004)*

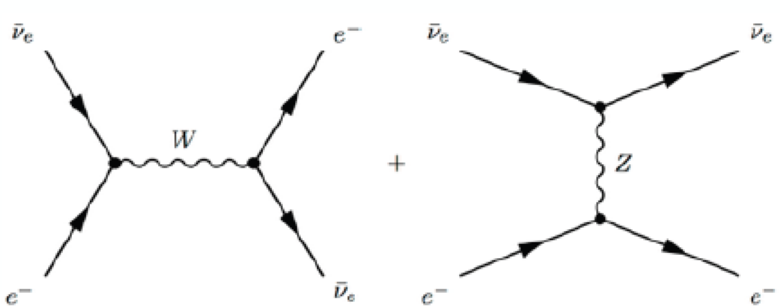


$$\overline{\nu}_e + p^+ \rightarrow e^+ + n$$



^{40}K geo-nus could contribute significantly to the 44 TW radiogenic heat of the earth, but have never been measured, since endpoint <1.8 MeV threshold for IBD

$$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$$



elastic scattering has no threshold, + direction of the out-going e$^-$ is correlated with the incident nu, can discriminate backgrounds from sun, reactors

Large, direction-sensitive detectors have potential to make the first observation of the ^{40}K flux, and perhaps to separate crust vs. mantle composition.

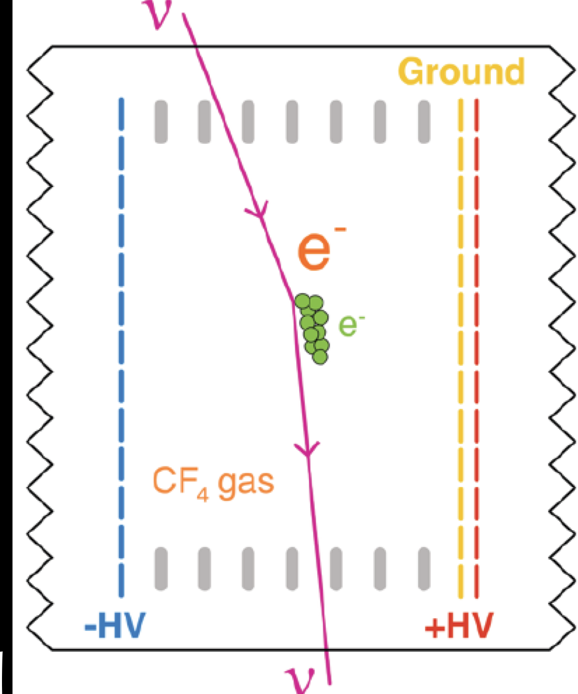
Geo-Neutrinos and Direction

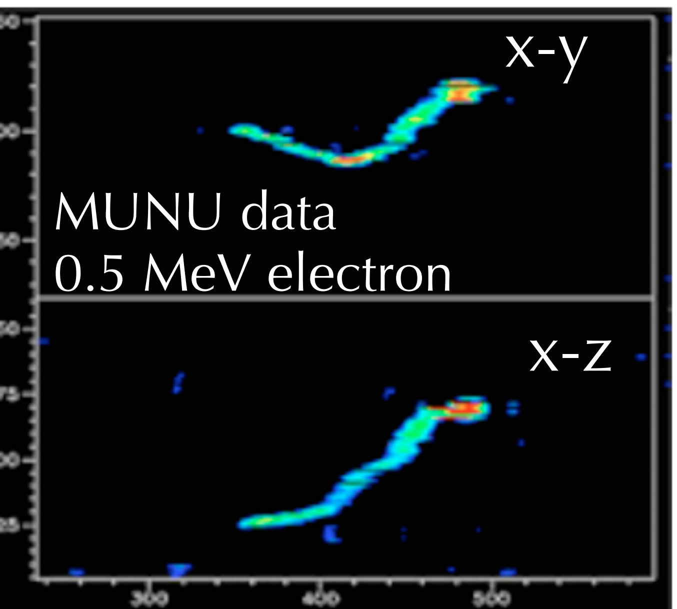
Measure the recoil e- direction to infer the nu direction.

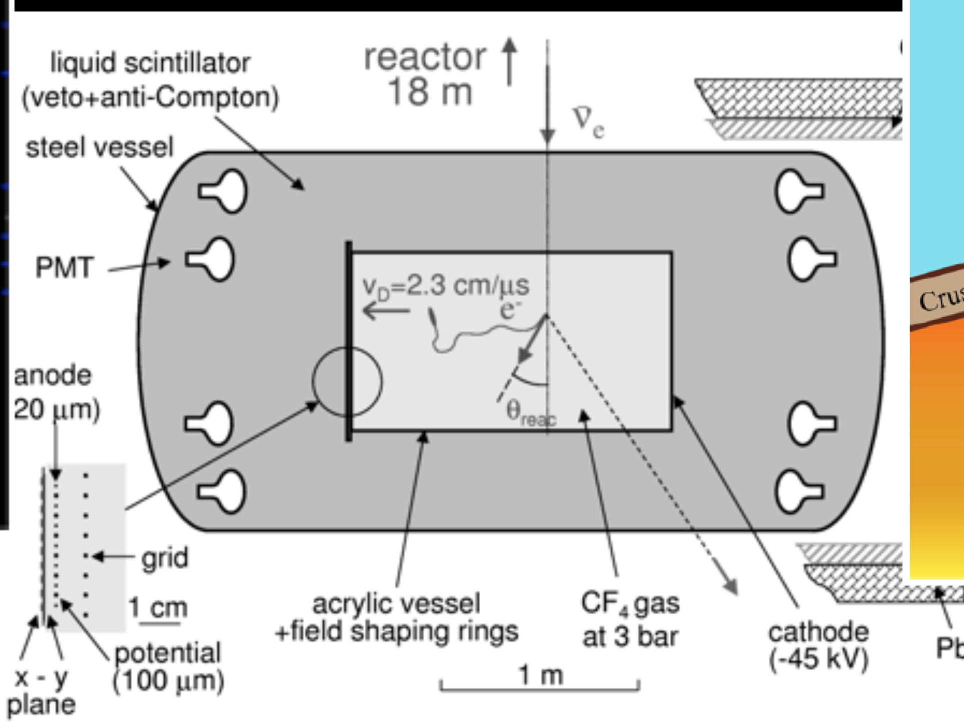
Example) MUNU measured e- from reactor nu-e scattering, with 50% efficiency, 12º-15º resolution above 200 keV, in CF_4 gas at 1 bar pressure, using MWPC + PMTs

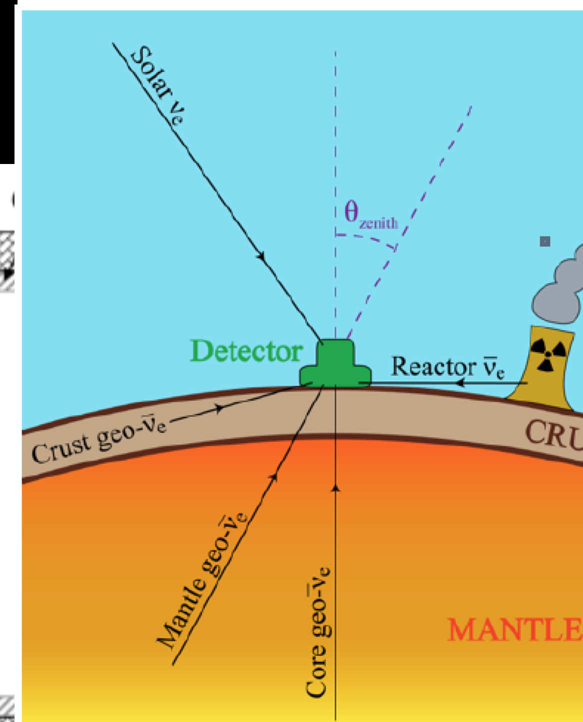
Daraktchieva et al., PLB 615, 153 (2005)

for DMTPC study, assume similar performance and threshold with detailed geo-nu flux model from PREM and CRUST 1.0



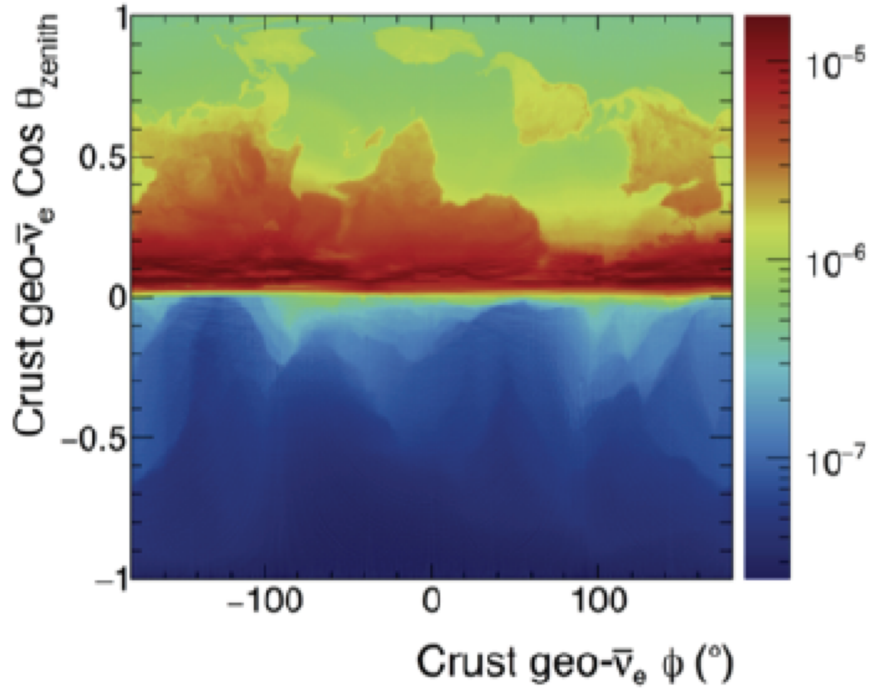


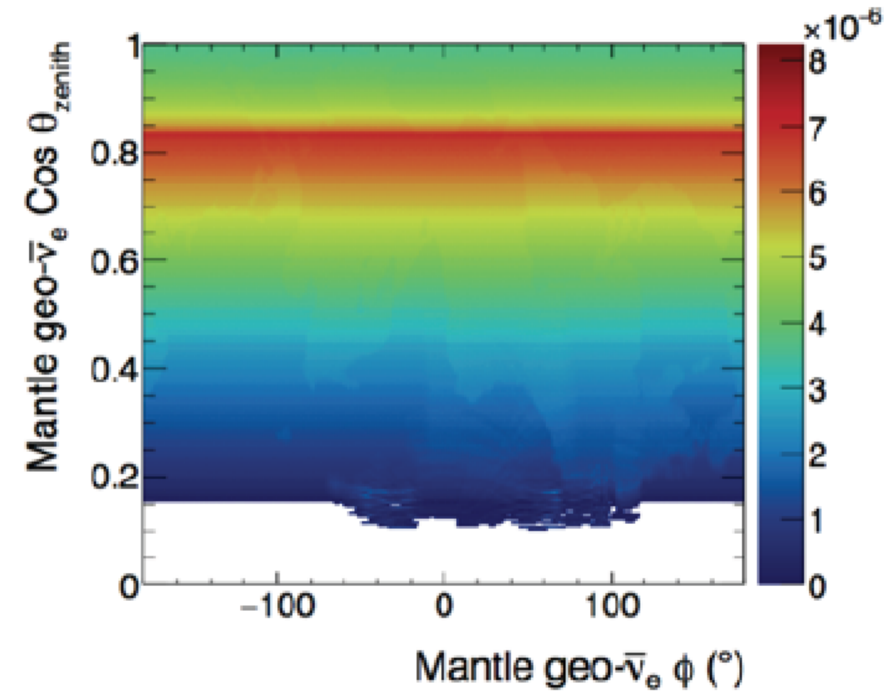




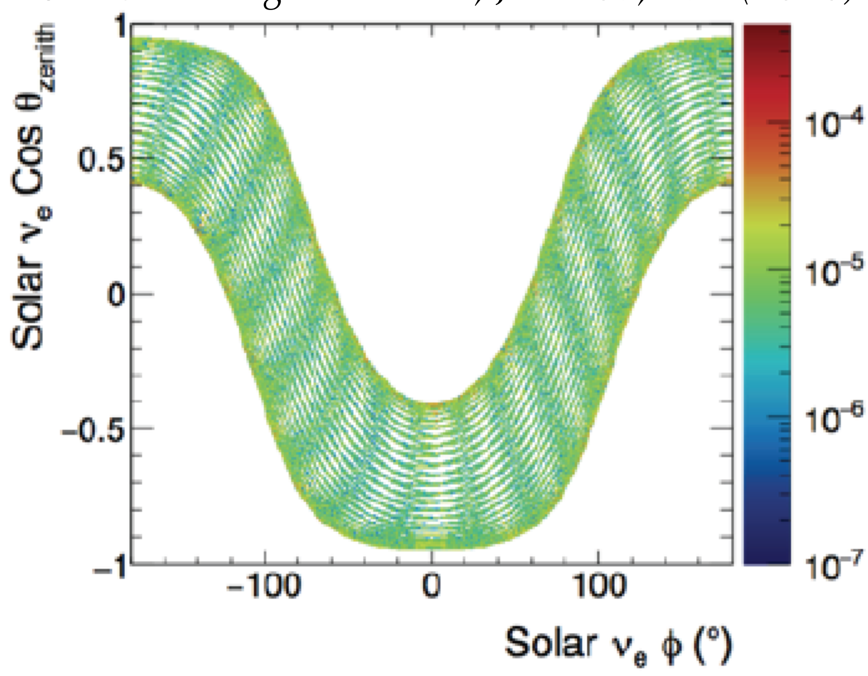
Incident Neutrino Flux

Leyton, Dye, JM, sub. Nature (2016)

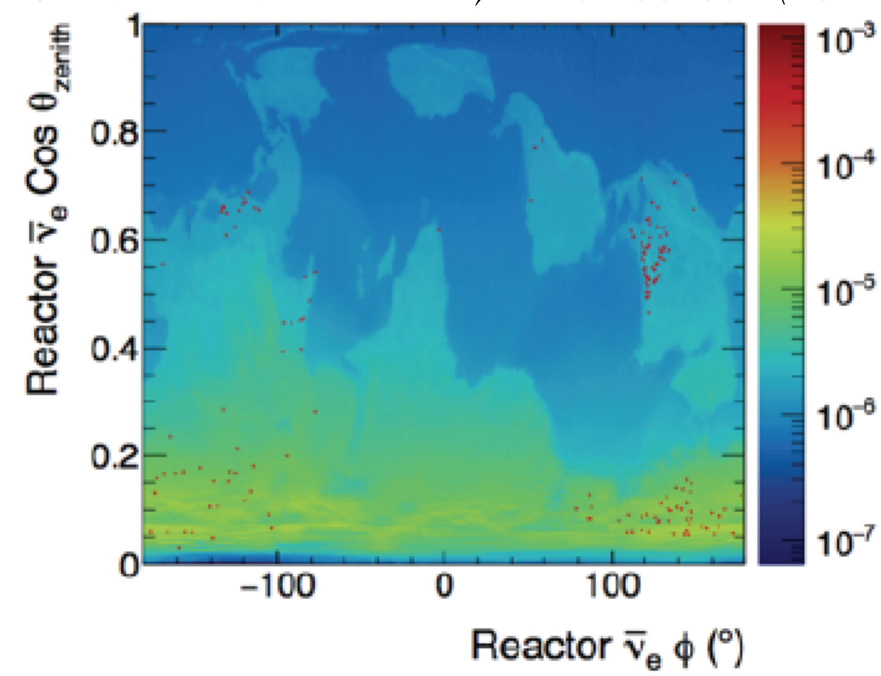




based on Bergstrom et al., JHEP 03, 132 (2016)



based on Baldoncini et al., PRD91 065002 (2015)

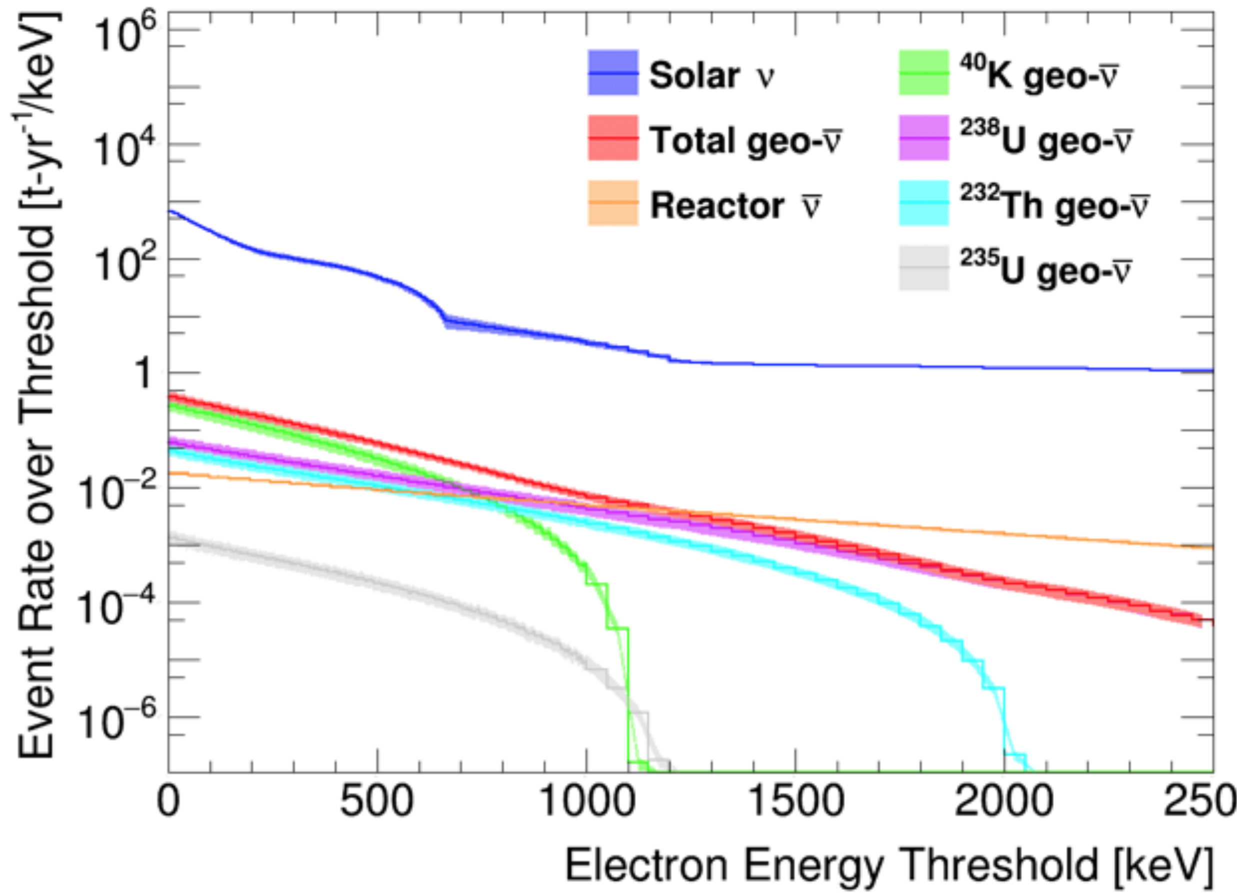


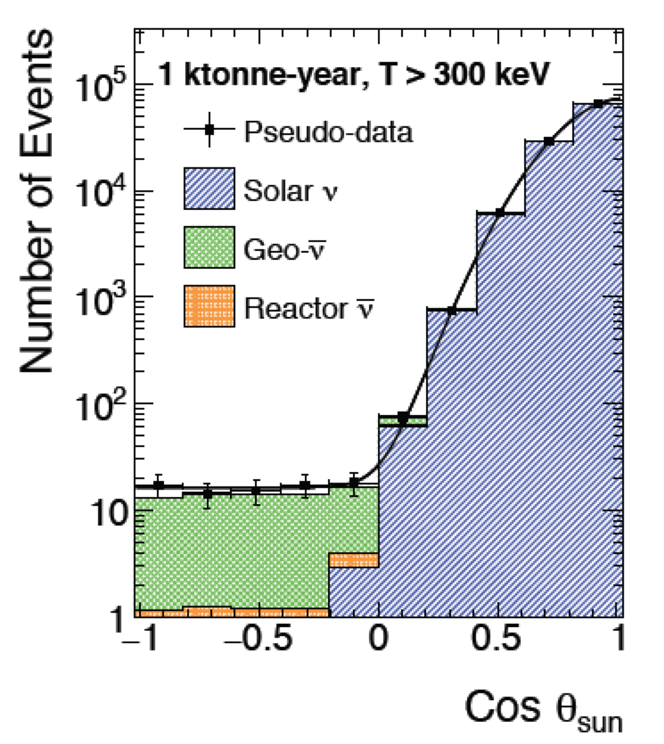
Scattering Rates

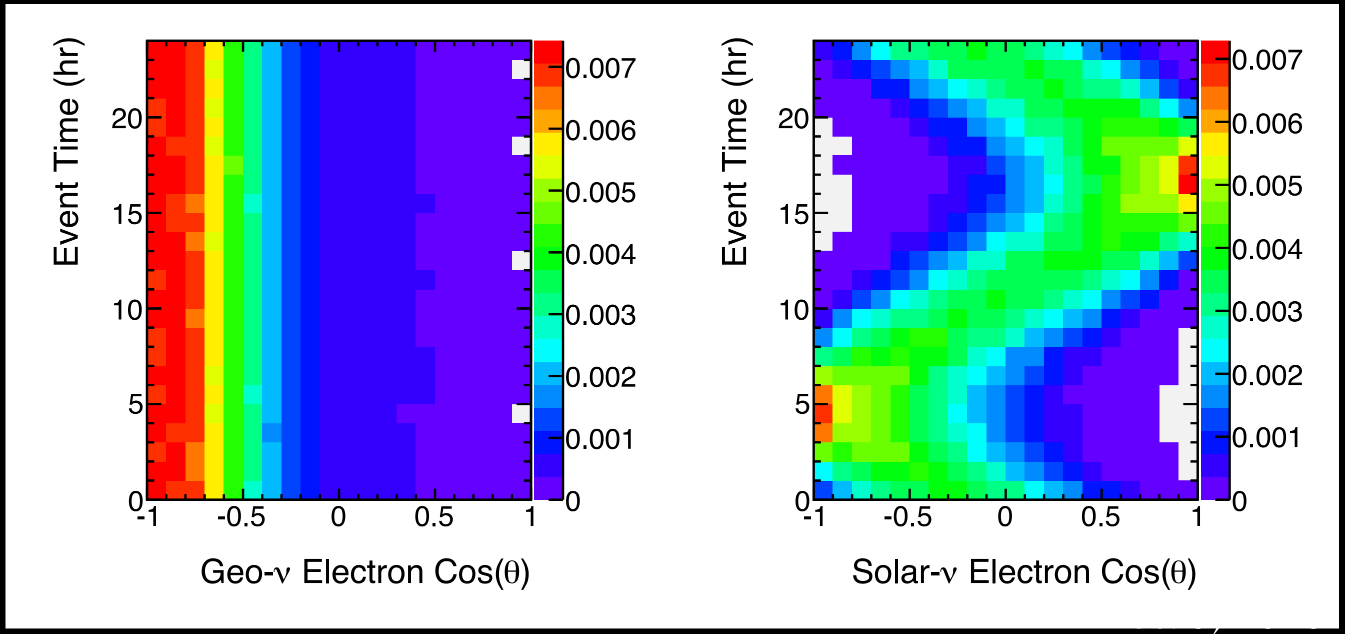
experiments use IBD because solar nu-e$^-$ elastic scattering backgrounds are large!

direction-sensitive low-energy TPCs can exploit angle, time, and energy spectrum differences

(CNO signal today = geo-nu bgnd tomorrow) *Bonvicini et al, NIM A 491 (2002)*







Geo-Neutrino Sensitivity

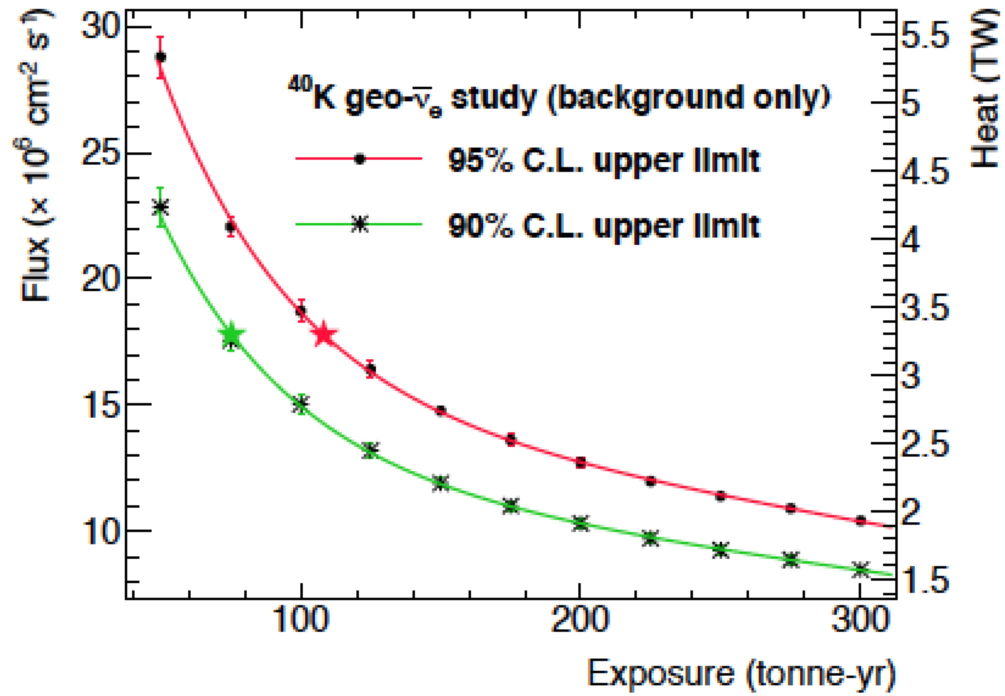
simulate 1000 toy experiments, use profile likelihood statistic to test

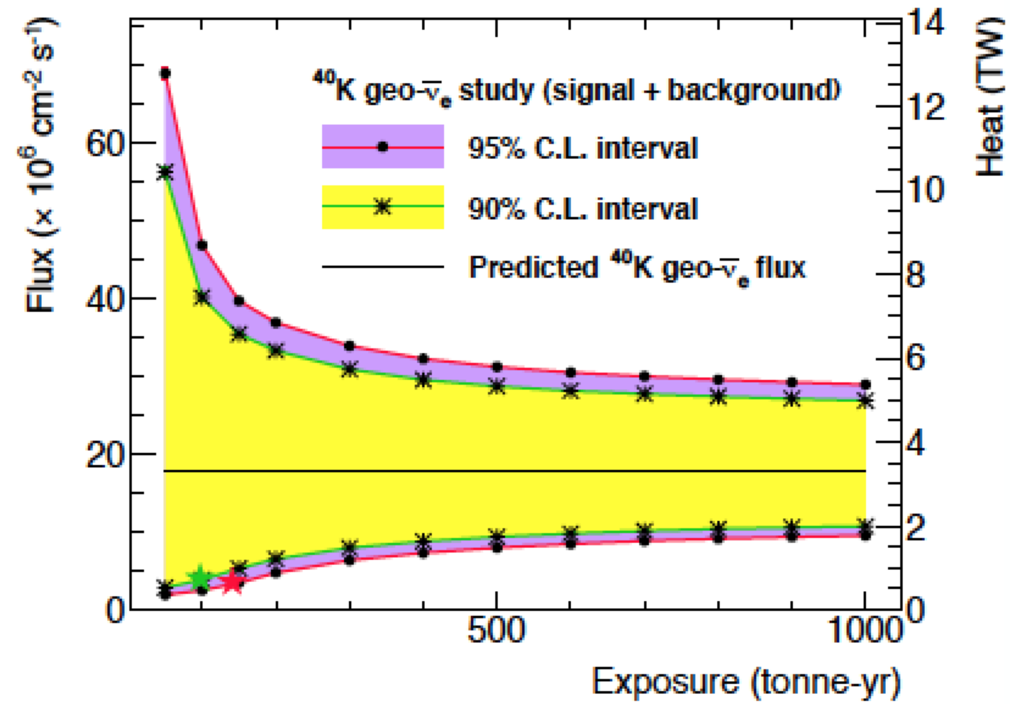
case (i): **no** ^{40}K signal in "data,"
find 90, 95% CL upper limit on ^{40}K flux

case (ii): **yes** ^{40}K signal in "data,"
find ^{40}K flux at which null hypothesis can be excluded at 90, 95% CL

studied signal = ^{40}K, mantle, core, reactor

	40K	Mantle (no radioactivity in core)	Core	Reactor monitoring
Energy threshold	200 keV	250 keV	800 keV	1.5 MeV
Solar-ν flux uncertainty	+11.2, -5.3 %	+12.3, -5.8 %	+20.0, -11.5 %	+2.2, -1.4 %
Geo-ν flux uncertainty	±18-20%	±11%	±5%	±18-20%
cos θ_{sun}	< -0.09	< 0.02	< 0.54	< 0.53
90% <UL> (tonne-yrs)	73-87	435-560	47000-53000	111-200
90% <CI> (tonne-yrs)	89-106	1051-1557	134000-138000	98-301



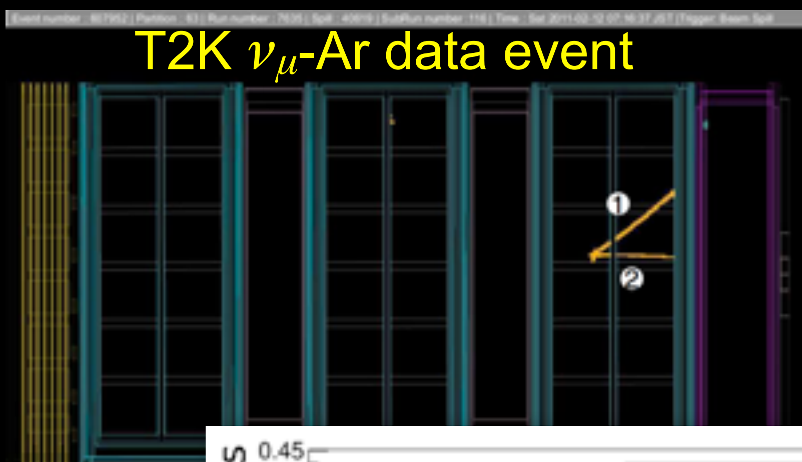


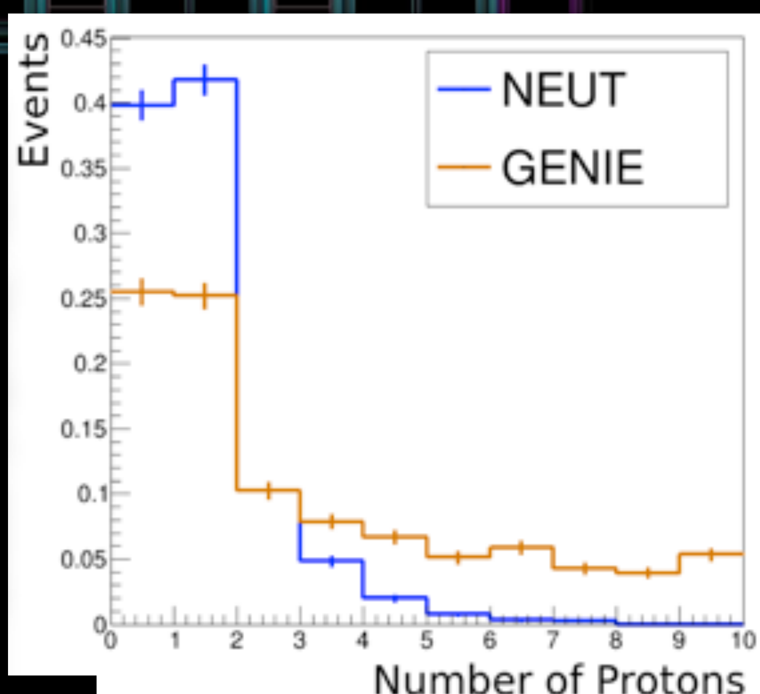
Connection with R&D for Accelerator Neutrino Oscillations

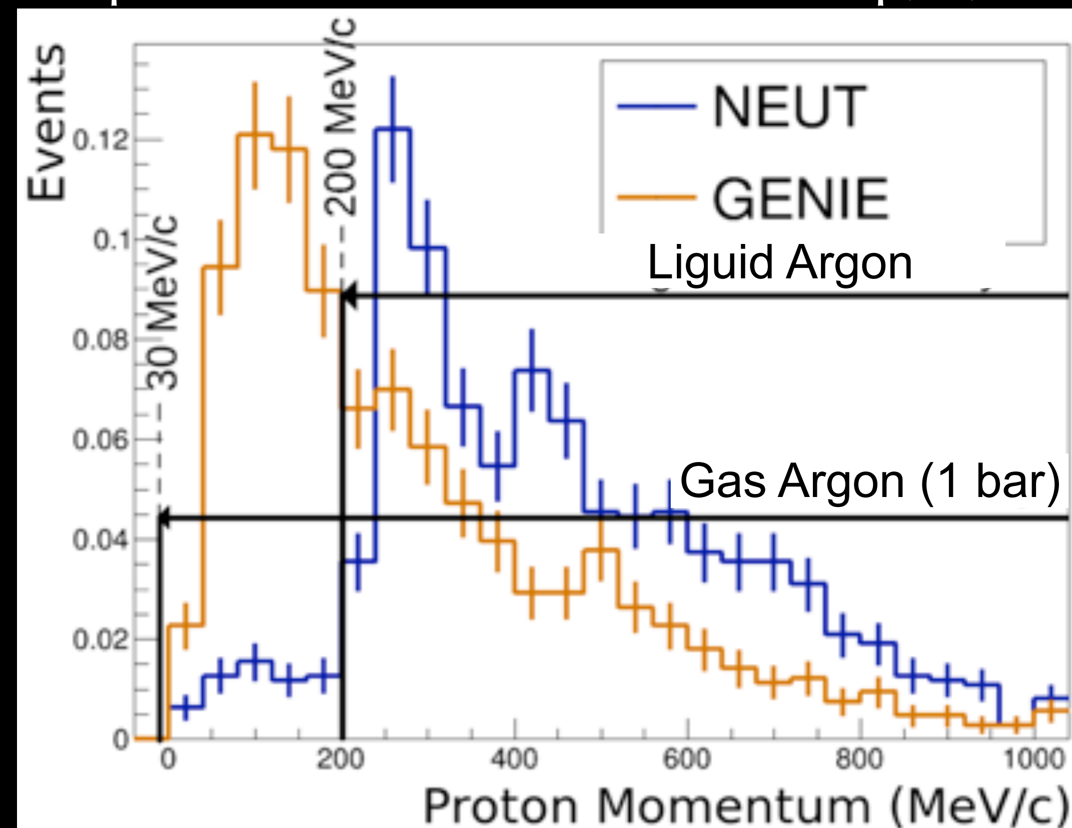
Low Threshold Gas TPC R&D for Neutrino Physics:

goal: reduce neutrino cross section systematics from 8-10% to 1-2% for CP violation search in long-baseline neutrino oscillation experiments, with 10 MeV threshold

- address nuclear model uncertainties with precision measurements of FS p, e, mu







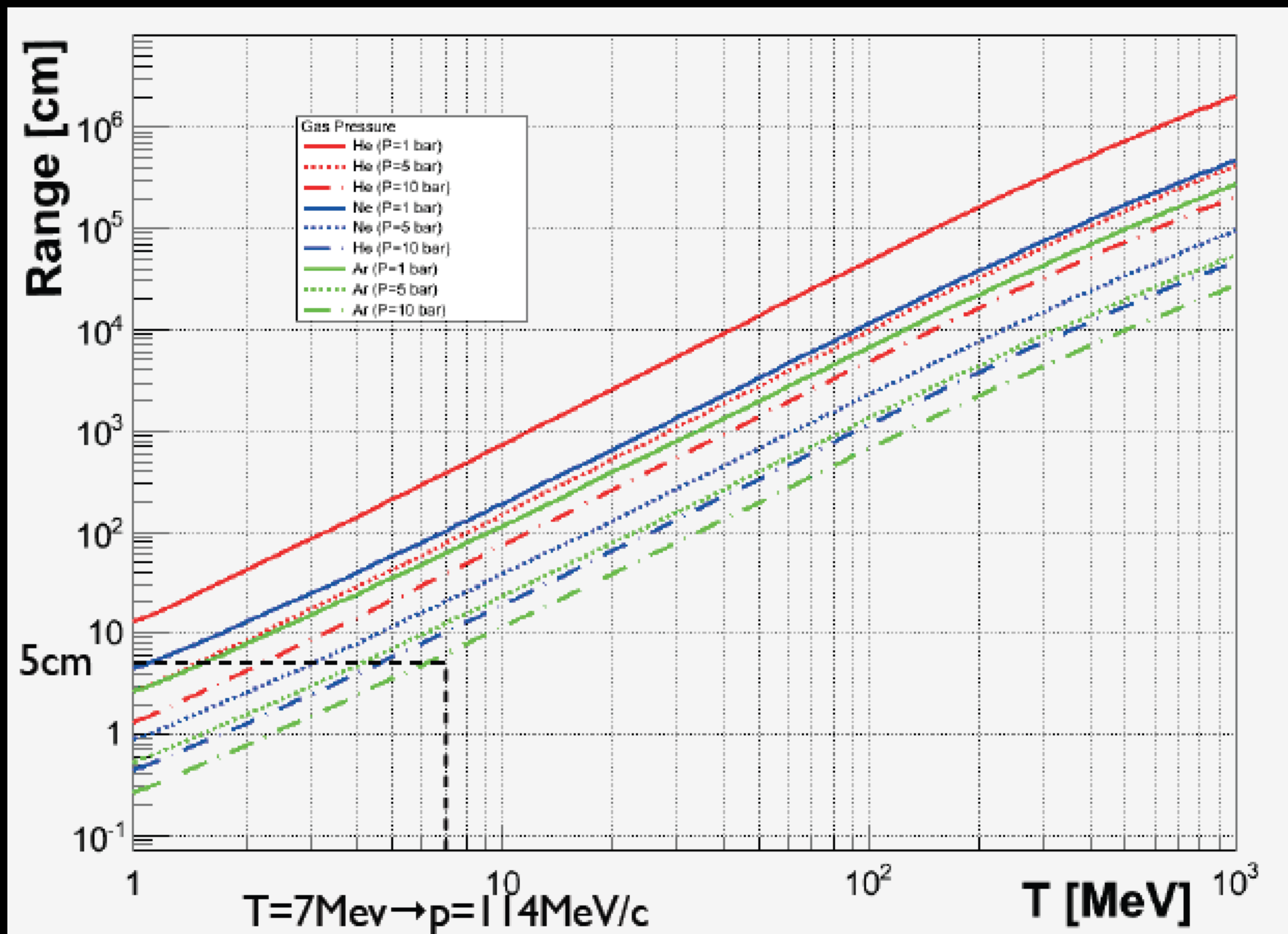
P. Hamilton (Imperial), NuInt14

- higher pressure needed!
  Example) 5E4 events for T2KII flux, in 40 m^3 detector volume at 5 bar CF_4.

Proton Range in HPTPC

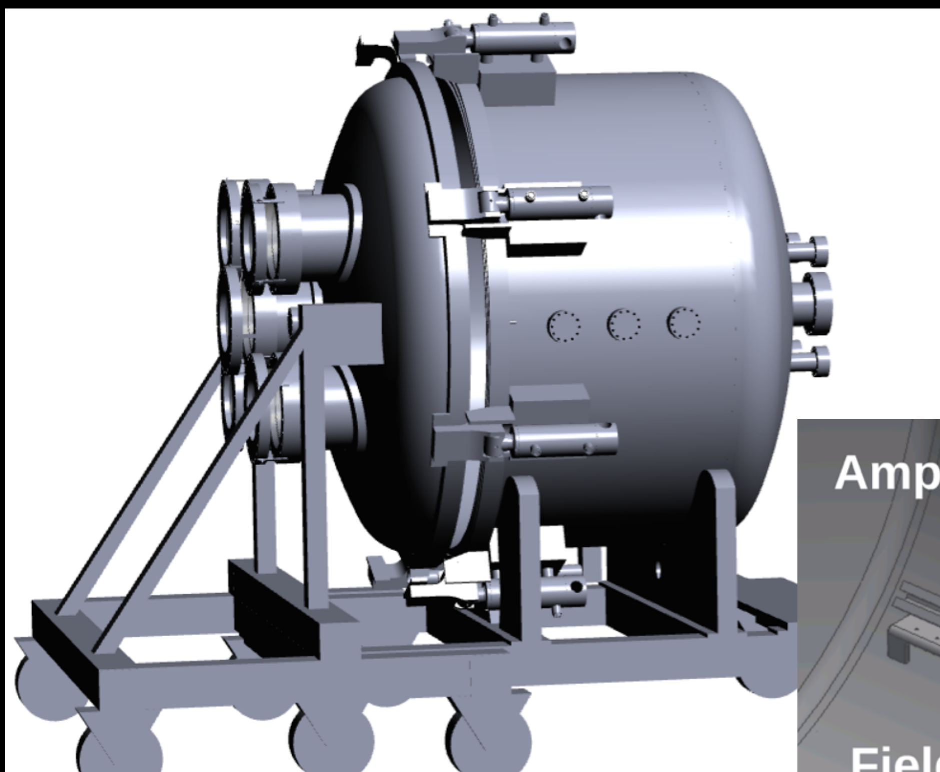
1 cm track reconstruction threshold gives ~50 MeV/c proton threshold in 5 bar Ar, sufficient to conclusively measure the problematic region in final state particle kinematics in neutrino interactions for long baseline oscillations.

1 cm range threshold -> ~1 mm readout pitch (and 10^2 x S:N for DMTPC)



HPTPC Prototype

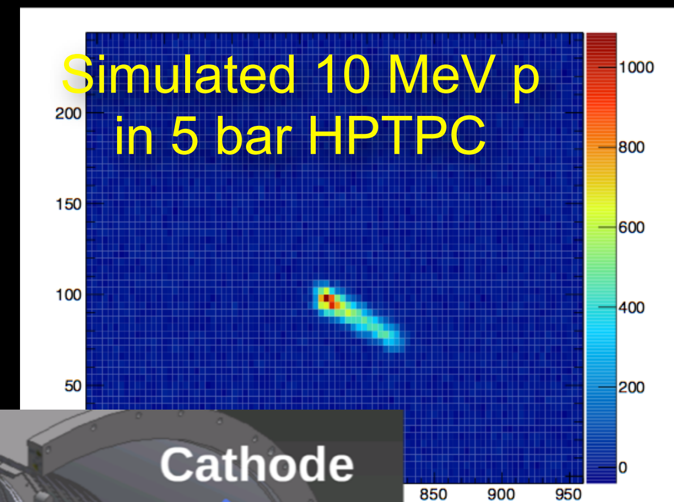
Pressure vessel capable of 5 bar operation with mixtures of CF_4, Ar, Ne, CO_2, CH_4. Optical readout based on DMTPC (0.5 mm optical plate scale), plan micromegas amplification structures with T2K TPC electronics (charge readout with ~cm pitch)

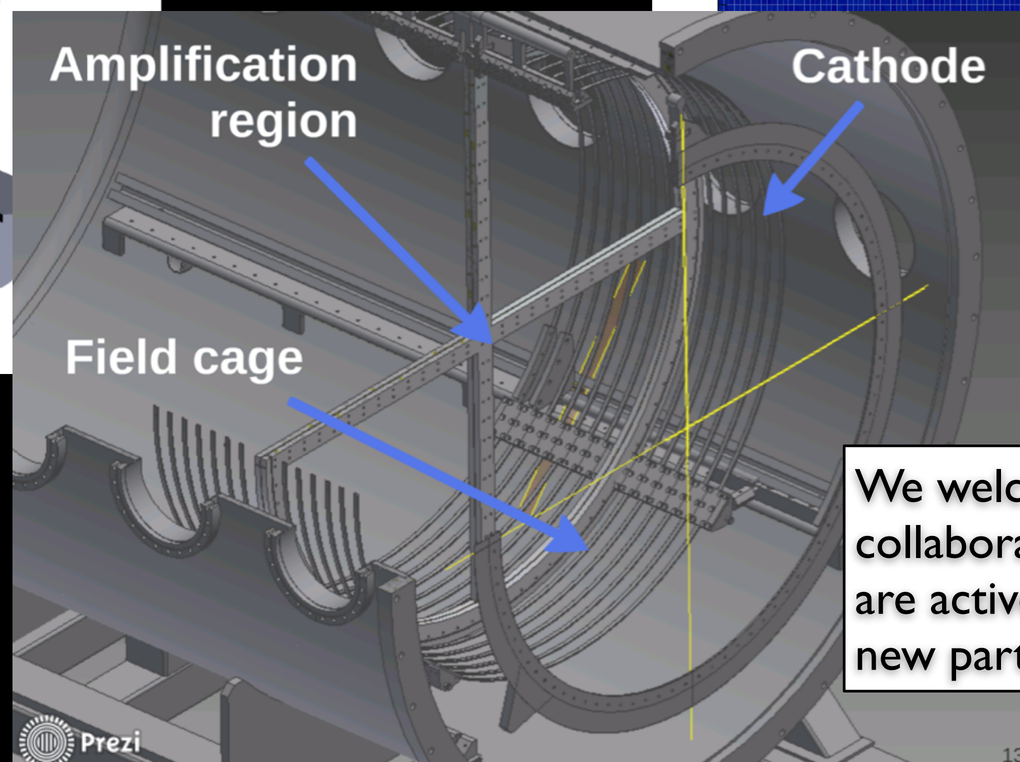


Pressure vessel delivery early '17.

50 cm drift length

1.2 m TPC diameter (// to beam direction)





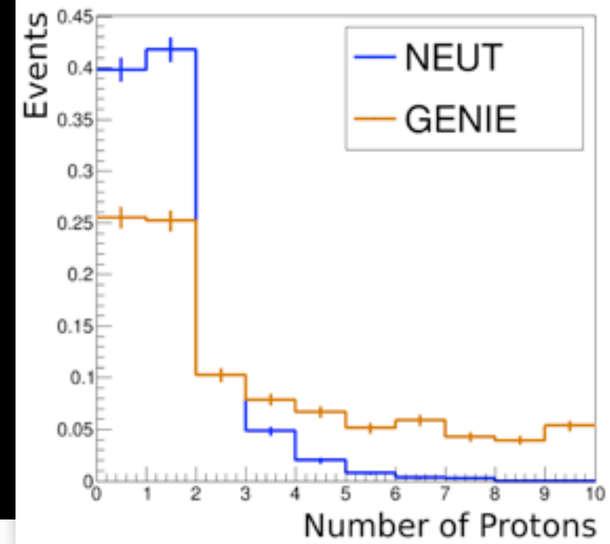
We welcome collaboration and are actively seeking new partners!

UK groups funded to build prototype for CERN beam test: ICL,RHUL,Warwick,Lancaster, + discussions with EU groups on participation in beam test

Beam Test: Proton-Nucleus Cross Section

no data in most of the relevant region for neutrino interactions in long baseline oscillation experiments

beam test goal: measure p absorption cross section, and final state multiplicity, in p-Ar, p-F interactions < 1 GeV/c



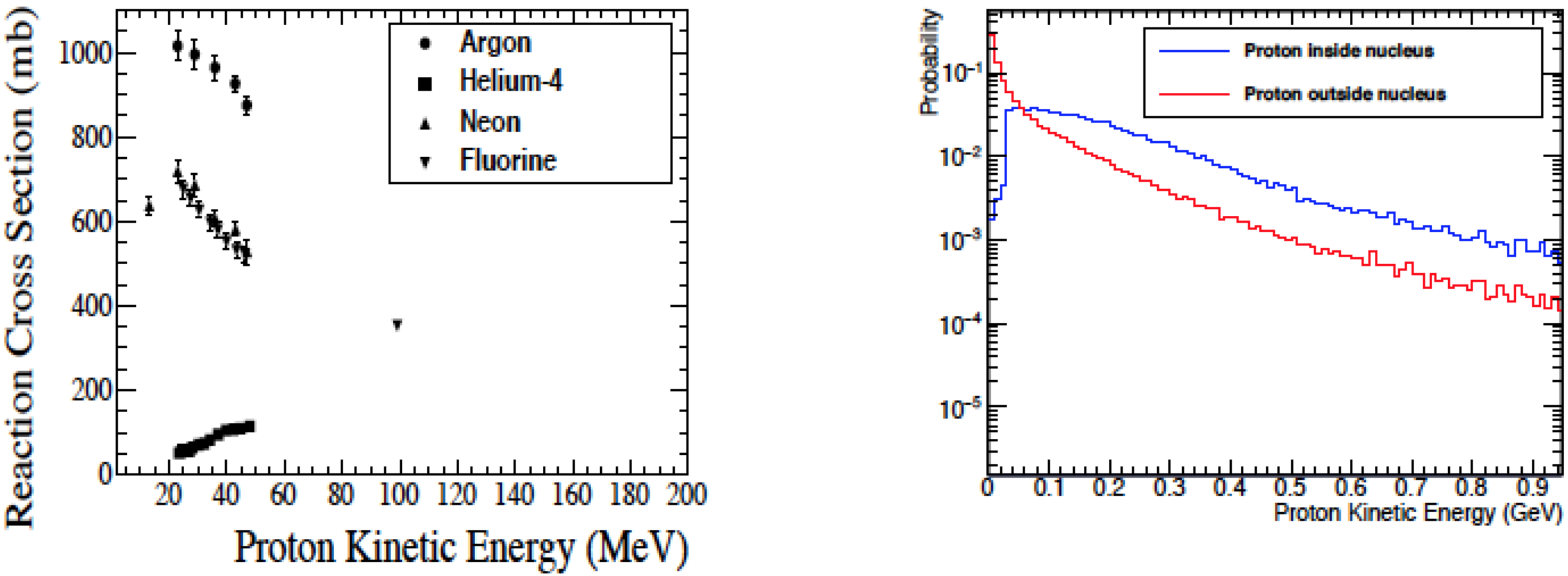


Figure 0.2.1: *Left: Total reaction cross sections for protons on four nuclei: argon, helium-4, neon, and fluorine. [Data compiled by A. Kaboth and W. Ma (Imperial PhD student).] Right: GENIE proton distributions for 600 MeV ν_μ-CC interactions on Ar before (blue) and after (red) final state interactions.*

Conclusions

- Optical TPC readout is a promising technology to get to sub-mm resolution at reasonable cost per channel in very large detectors.

- DMTPC has demonstrated <40^{o} angular resolution with 25 cm diffusion, recovering the intrinsic directionality of the recoil to the straggling limit

- In the process of moving from small prototypes to 'physics-scale' detector module. Commissioning of DMTPCino underway...
  - demonstrated 4x increase in gas gain
  - coincident readout of charge (fast, slow), light (fast, slow) signals powerful for background rejection.
    - *main challenge*: achieve resolution + head-tail, at lower energy

- Exploring applications to neutrino scattering physics, looks promising for geo- and accelerator- neutrinos, new collaborators very welcome to get involved!